VOL THREE / *ISSUE* ONE

NewScientist THE COLLECTION

THE WONDERS OF SPACE

A FANTASTIC JOURNEY THROUGH THE MOST MIND-BLOWING SIGHTS IN THE COSMOS

THE SUN / THE MOON / MARS / PLUTO

BLACK HOLES / THE MILKY WAY / COMETS / TITAN

EXOPLANETS / SUPERNOVAE / QUARK STARS

PLUS HUBBLE'S BEST IMAGES

£9.99

9 772054 638003 01


Professor Dame Carol Robinson
2015 Laureate for United Kingdom
By Brigitte Lacombe
For Women in Science
FONDATION L'ORÉAL
Science needs women
L'ORÉAL UNESCO AWARDS
Dame Carol Robinson, Professor of Chemistry at Oxford University, invented a ground-breaking method for studying how membrane proteins function, which play a critical role in the human body.
Throughout the world, exceptional women are at the heart of major scientific advances.
For 17 years, L'Oréal has been running the L'Oréal-UNESCO For Women In Science programme, honouring exceptional women from around the world. Over 2000 women from over 100 countries have received our support to continue to move science forward and inspire future generations.
JOIN US ON FACEBOOK.COM/FORWOMENINSCIENCE

NewScientist
THE COLLECTION

VOL 3 / ISSUE 1
THE WONDERS OF SPACE

NEW SCIENTIST THE COLLECTION
110 High Holborn,
London WC1V 6EU
+44 (0)20 7611 1202
enquiries@newscientist.com

Editor-in-chief Graham Lawton
Editor Gilead Amit
Art editor Craig Mackie
Picture editor Prue Waller
Subeditor Vivienne Greig
Graphics Dave Johnston
Production editor Mick O'Hare
Project manager Henry Gomm
Publisher John MacFarlane

New Scientist The Collection is published five times per year by Reed Business Information Ltd
ISSN 2054-6386

Printed in England by Williams Gibbons (Wolverhapton) and distributed by Marketforce UK Ltd
+44(0)20 3148 3333

Cover image
NASA/JPL/Space Science Institute

An incredible journey

IN OCTOBER 1604, something remarkable appeared in the night sky. Without warning, a light brighter than any star suddenly lit up the darkness. Early astronomers saw it as a miraculous portent of things to come. None of them guessed what it really was – the dying light of a distant star that had exploded thousands of years before.

Now known as Kepler's Star after the astronomer who watched it for more than a year, the supernova helped to usher in a new era of space exploration. Within a few years Galileo Galilei was pioneering the use of the telescope, using one he'd designed himself to observe hills and valleys on the moon, spots on the sun, the phases of Venus, the stars of the Milky Way and, most famously, the satellites of Jupiter. Tycho Brahe, Christiaan Huygens and other greats of early astronomy were soon making discoveries of their own.

We are still in the golden age of discovery kick-started by these pioneers. We now have telescopes the size of football fields peering deeper into space than Kepler could have imagined. And for the past 60 years we have been sending satellites, craft, probes, humans and instruments into space to get an even closer look. Right now, the Curiosity rover is sending back snapshots from the surface of Mars and the Philae lander is hitchhiking out of our solar system aboard a passing comet.

Thanks to these tools of exploration our knowledge of the cosmos is constantly expanding all the time. As just one example, when the European Space Agency's Gaia mission finishes in 2018, its telescope will have photographed over a billion stars, providing us with the most accurate three-dimensional map of the heavens ever drawn. The memory of the swashbuckling race to the moon may be fading, but space exploration is as vibrant as ever.

This issue of *New Scientist: The Collection* roams the frontiers of that inspirational quest. It will illuminate some of the deepest mysteries of the universe and help you see our own cosmic corner in astonishing detail.

Chapter 1 takes a journey around our solar system. Meet the robots climbing the mountains of Mars, visit some of our neighbourhood's most unusual moons, stare at the surface of the sun and get to know the spacecraft struggling to cross the solar system's last horizon.

Chapter 2 widens the aperture to explore our home galaxy, the Milky Way. We no longer think it is the entire universe, but still many of its secrets elude us, from the black hole at its centre to the stars that may have formed alongside our sun.

Chapter 3 returns to more familiar – if still very alien – territory in the shape of the Earth-like planets that may be strewn across the cosmos. What strange worlds are they? Are they – or their moons – capable of supporting intelligent life? And how would we know what to look for?

Finally, Chapter 4 plunges into the depths of space to check out some of its most unusual inhabitants, from the galaxies too perfect to exist to the stars larger than we thought possible.

We may no longer rely on the naked eye to scan the heavens, but there's plenty we still don't know. Let *New Scientist* take you to the very limits of our knowledge, and guide you through the questions that will power the next centuries of discovery.

Gilead Amit, Editor

CONTENTS

NewScientist
THE COLLECTION

CONTRIBUTORS
Anil Ananthaswamy is a consultant for *New Scientist*
Jacob Aron is a reporter for *New Scientist*
Stephen Battersby is a consultant for *New Scientist*
Rebecca Boyle is a freelance writer based in St Louis, Missouri
David L. Chandler is a science writer based in Boston, Massachusetts
Marcus Chown is a consultant for *New Scientist*
Stuart Clark is a consultant for *New Scientist*
Rachel Courtland is a science writer based in New York City
Ken Croswell is an astronomer and author based in California
Sarah Cruddas is a space journalist and broadcaster based in London
Will Gater is an astronomy journalist based in Somerset, UK
Ben Gilliland is editor of *Astronomy Now* magazine
Adam Hadhazy is a freelance writer based in New Jersey
Sophie Hebden is a writer based in Mansfield, UK
Nigel Henbest is a freelance writer based in Buckinghamshire, UK
Dana Mackenzie is a freelance writer based in Santa Cruz, California
Brian Owens is a freelance writer based in St Stephen, Canada
Andy Ridgway is a science writer based in Bristol, UK
Joshua Sokol is a freelance writer in Boston, Massachusetts
Colin Stuart is a freelance astronomy writer based in London
Vanessa Thomas is a science writer based in Baltimore, Maryland
Richard Webb is features editor at *New Scientist*

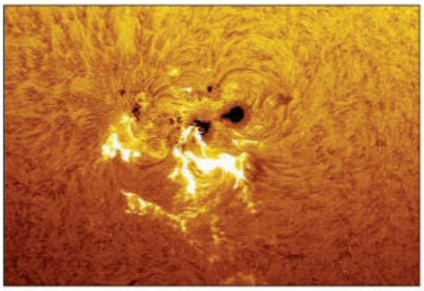
The articles here were first published in *New Scientist* between January 2009 and November 2015. They have been updated and revised.

VOL 3 / ISSUE 1

THE WONDERS OF SPACE

1

The solar system



2

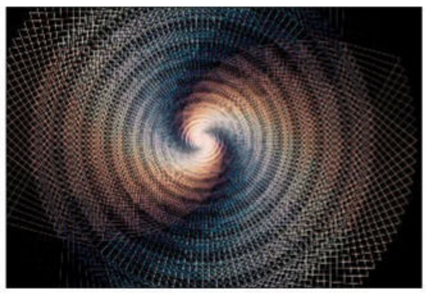
The Milky Way

3

Exoplanets and aliens

4

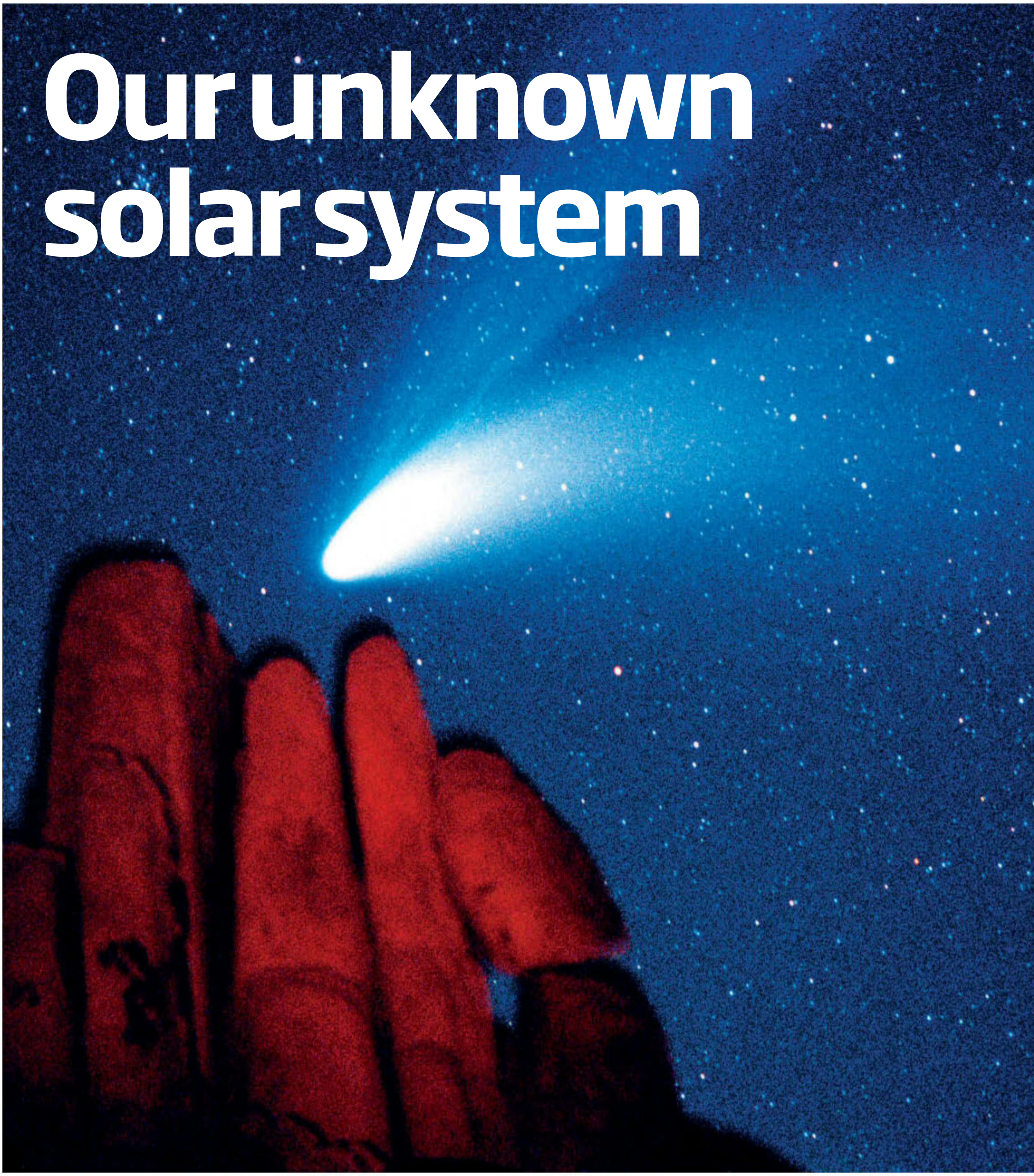
Space oddities




News
After handshakes, we sniff people's scent on our hand
After handshakes, we sniff our hand
YouTube
This suggests that handshakes might transmit chemical signals
You won't believe you do it, but you do. After shaking hands with someone, you'll lift your hands to your face and take a deep sniff. This newly discovered behaviour – revealed by covert filming – suggests that much like other mammals, humans use bodily smells to convey information.
We know that women's tears transmit chemosensory signals - their scent lowers
Free sample issues


New Scientist
See science everywhere
Enjoy free sample issues within the app
Download the *New Scientist* app today
Available on the App Store
ANDROID APP ON Google play
Download from Windows Store

Our unknown solar system



WALTER PACHOLKA/ASTROPICS/SPL

ONCE upon a time, 4.6 billion years ago, something was brewing in an unremarkable backwater of the Milky Way. The ragbag of stuff that suffuses the inconsequential, in-between bits of all galaxies – hydrogen and helium gas with just a sprinkling of solid dust – had begun to condense and form molecules. Unable to resist its own weight, part of this newly formed molecular cloud collapsed in on itself. In the ensuing heat and confusion, a star was born – our sun.

We don't know exactly what kick-started this process. Perhaps, with pleasing symmetry, it was the shock wave from the explosive death throes of a nearby star. It was not, at any rate, a particularly unusual event. It had happened countless times since the Milky Way itself came into existence about 13 billion years ago, and in our telescopes we can see it still going on in distant parts of our galaxy today. As stars go, the sun is nothing out of the ordinary.

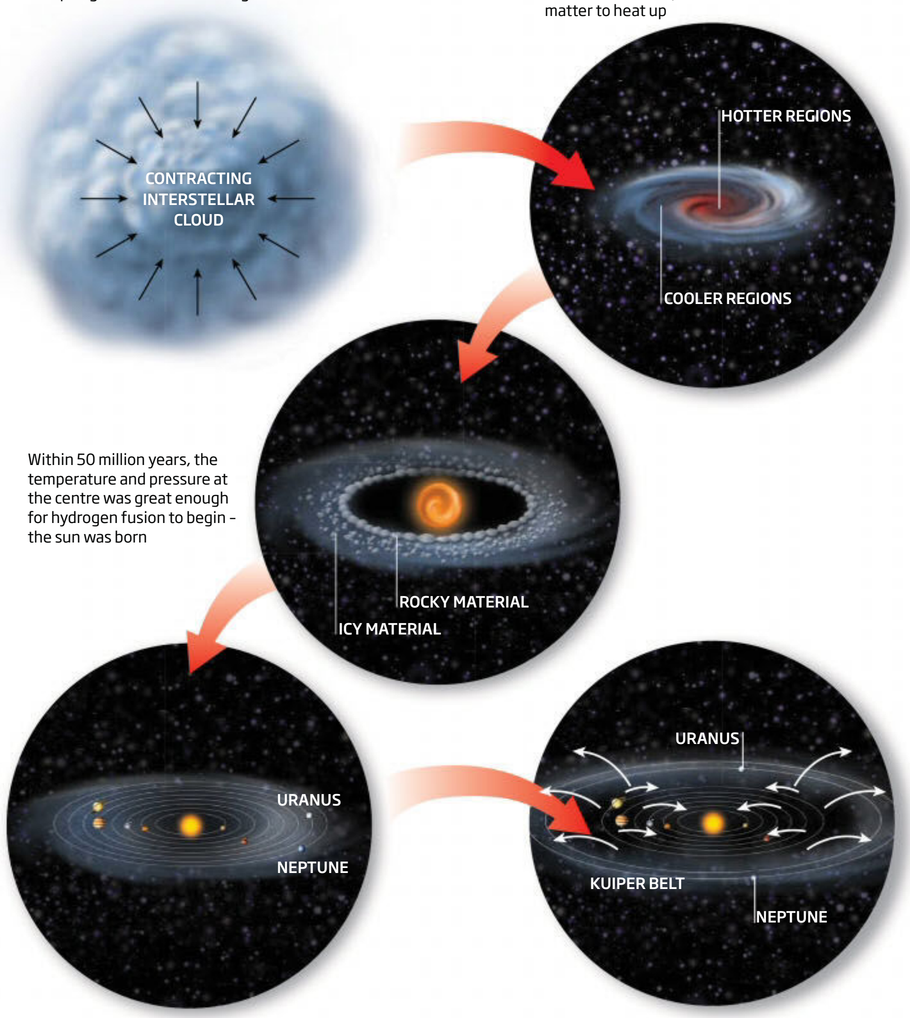
And yet, as far as we know, it is unique. From a thin disc of stuff left over from its birth, eight planets formed, trapped in orbit by its gravity. One of those planets settled into a peculiarly tranquil relationship with its star and its fellow planets. Eventually, creatures emerged on it that began to wonder how their neighbourhood came to be as it is – and could formulate the following enduring questions about our familiar, and yet deeply mysterious, solar system.

How was the solar system built?

Looking at the planets of the solar system, you could be forgiven for thinking that if they do belong to the same family, it is by adoption rather than kinship. Not so: the story of the solar system's birth reveals that they are blood siblings, all created from the same molecular cloud whose collapse formed the sun. You might also think that these disparate bodies are scattered across the solar system without ›

How to make a solar system

We think we know the story of the solar system, but only comparison with other systems can tell us if that story is universal



4.6 billion years ago, an area of gas and dust in the Milky Way started to condense, collapsing in under its own weight

The result was a thin, rotating disc of material. In the centre, where most of the mass was concentrated, frequent collisions caused the matter to heat up

Within 50 million years, the temperature and pressure at the centre was great enough for hydrogen fusion to begin – the sun was born

100 million years in, the accretion of smaller bodies had largely created the solar system planets we see today, surrounded by a rim of non-accreted icy material. The precise orbits of the planets are unknown

Several hundred million years in, an interaction of Jupiter and Saturn caused Uranus and Neptune to migrate outwards, scattering rim material in all directions. Some bombarded the inner planets, some was ejected to form the Oort cloud and the remainder formed the Kuiper belt

REV RONALD ROYER/SPL

rhyme or reason. But move any piece of the solar system today, or try to add anything more, and the whole construction would be thrown fatally out of kilter. So how exactly did this delicate architecture come to be?

When our sun formed, it swallowed about 99.8 per cent of the debris cloud around it. According to the generally favoured picture, the lean pickings that remained were sculpted by gravity into a thin disc of gas and dust encircling the newborn star's midriff (see illustration, above). As the dust grains of this disc orbited the sun, they collided and progressively coagulated into ever larger bodies. In the disc's innermost region, the ignition and burning of hydrogen in the sun made things very hot, so that only metals and silicate minerals with high melting points were present in solid form. Bodies in that region could only reach a certain size – producing the four small rocky planets of the inner solar system: Mercury, Venus, Earth and Mars.

No such stringent limitations existed further out, beyond the "ice line" where methane and water are also present as solids. Here, the developing planets could grow bigger, and become large enough to start accreting gas molecules – mainly hydrogen – before energy from the sun's increasingly powerful glare ripped those molecules apart. That, ultimately, was how the gas giants Jupiter and Saturn came to be and, further out in still colder climes, the ice giants Uranus and Neptune. That is the reason astronomers expect these planets too to possess rocky hearts beneath their fluid coats.

So far, so straightforward. But when it comes to certain details, the accretion model becomes rather hand-wavy, says Alessandro Morbidelli of the Côte d'Azur Observatory in Nice, France. For a start, no one really knows exactly how metre-sized boulders coalesced into bodies tens of kilometres across. Solid objects that small would have been buffeted around by the pressure of the gas surrounding them and sent spiralling into the sun before they could ever get together. One promising idea proposes that local patches of turbulence in

Why are the sun and moon the same size in the sky?

It is one of the most glorious pieces of natural theatre. Assuming you spend your life on the same part of the Earth's surface, you might witness it once – if you are particularly lucky or very long-lived, perhaps twice. But a total solar eclipse is worth the wait. At the height of totality, the fit of sun and moon is so perfect that beads of sunlight can only penetrate to us through the rugged valleys on the lunar surface, creating the stunning "diamond ring" effect.

It is all thanks to a striking coincidence. The sun is about 400 times as wide as the moon, but it is also 400 times further away. The two therefore look the same size in the sky – a unique situation among our solar system's eight planets and 166 known moons. Earth is also the only planet to harbour life. Pure coincidence?

Almost undoubtedly, say most astronomers. But perhaps it is not so much of one as the bare numbers suggest. Our moon is different. The many moons of the large outer planets – Jupiter, Saturn, Uranus and Neptune – are thought to have originated through one of two processes: from the accretion of a disc of material in the planet's gravity field, in a miniature version of the formation of the solar system's planets, or through the later gravitational capture of passing small bodies. The second possibility is also thought to account for Mars's two small satellites, Deimos and Phobos, the only other moons in the inner solar system.

But our moon is simply too big relative to Earth's own size to have formed easily by either of these processes. Planetary scientists believe there can be only one explanation: in the first 100 million years of the solar system, when unattached debris was still zinging around the inner solar system, a Mars-sized object smashed into Earth. That impact radically remodelled our planet, expelling a huge amount of debris that eventually congealed into our oversized moon.

And here's the best bit. Such a big moon is a big boon for life on Earth. As Earth spins on its own axis, it has a natural tendency to wobble, owing to the varying pull on it from other bodies such as the sun. The unseen hand of the moon's gravity gently damps that wobble, preventing rotational instabilities which would otherwise have caused dramatic changes in Earth's climatic zones over time. Such instabilities would have made it much more tricky for life to get started on our planet.

Earth's position in the "habitable zone" around the sun where liquid water is abundant is undoubtedly the single most important factor in its fecundity. But the presence of a large moon – one large enough to cause total eclipses – might also have been crucial. If so, that has important consequences for the search for life on other planets.

Since the impact that created it, the moon has been moving steadily away from us, currently about 3.8 centimetres per year. The dinosaurs did not see eclipses like we do: the moon was too close 200 million years ago, more than big enough in the sky to block out the entire sun. Equally, any occupants of Earth in a couple of hundred million years' time will not see total eclipses at all, as the moon will appear too small.

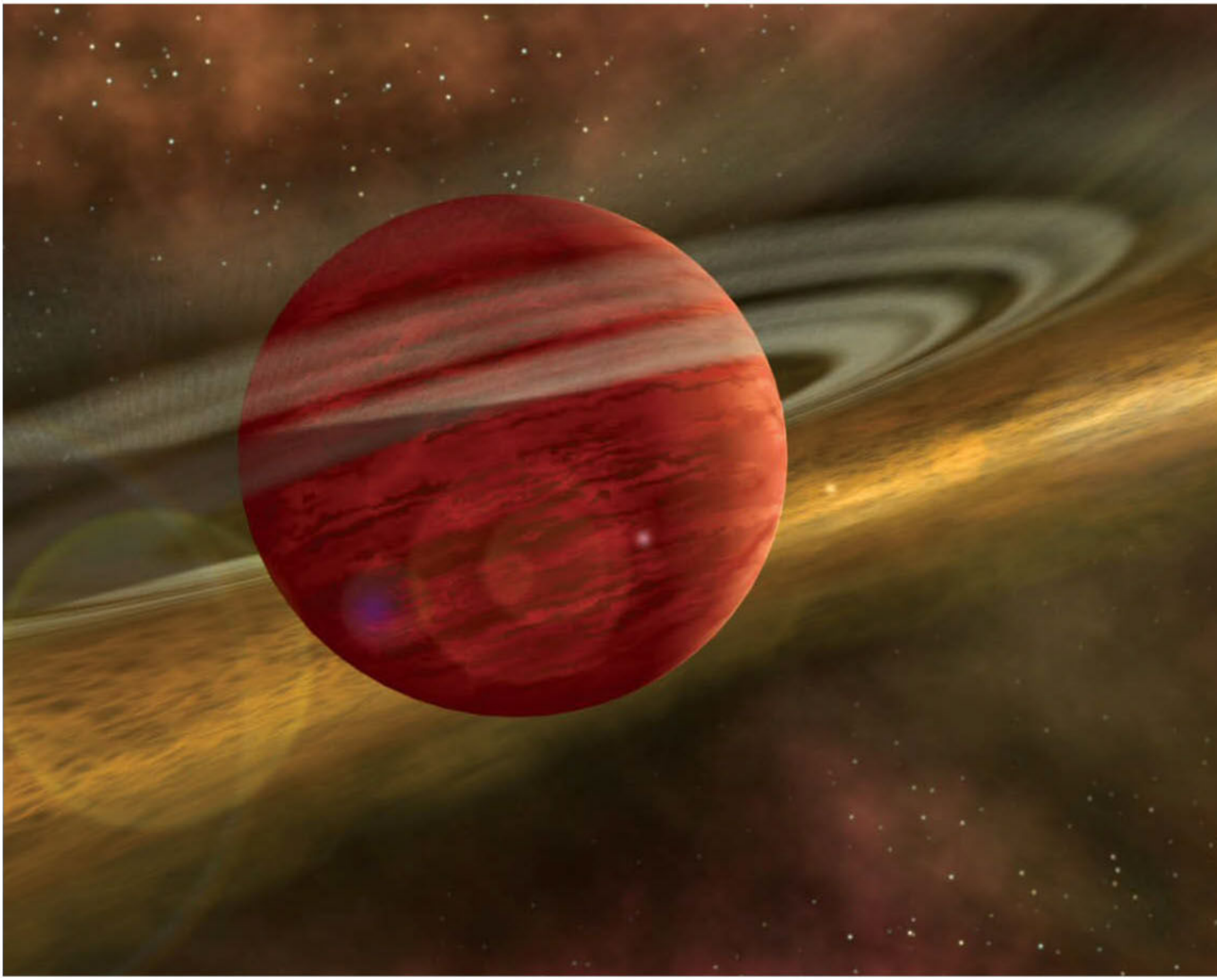
Our luck seems the result of two coincident timescales: that of the recession of an impact-formed moon, and that for the evolution of intelligent life. If you should be fortunate enough to experience a total eclipse in your lifetime, consider this intriguing possibility: that large moon might be the reason you are there. Marcus Chown

the gas provided vortices of lower pressure in which the boulders could collect and coagulate.

A similar problem bedevils the gas giants, whose solid cores must have coalesced in the presence of gas they would later accrete. The risk of such planets being bounced towards the sun is illustrated by the "hot Jupiters" seen in other planetary systems. These are planets roughly the size of Jupiter but orbiting around their stars at the distance of Earth or closer. Had anything like that happened in the early years of our solar system, the Earth and other inner planets could well have been slingshotted out of the solar system altogether – although that's no certain conclusion.

According to Phil Armitage of the University of Colorado in Boulder, there's not much sign of any such drama in our neighbourhood. If evidence such as our overlarge moon is any indication, the inner solar system did remain a choppy place for its first 100 million years as the rocky planets consolidated, but it soon settled down. And according to a theory developed by Morbidelli and colleagues, there was a rearrangement and expansion of the outer solar system a few hundred million years after the sun was born, when a particular conjunction of the orbits of Jupiter and Saturn gave a gravitational shove that propelled Uranus and Neptune out to the distant orbits they occupy today. Some of the small bodies that scattered on the way fell back towards Jupiter, whose immense gravity may have ejected some of them from the solar system. Deep in space, these unaccreted fragments collected as the hypothetical Oort cloud.

The knock-on effect of this last gravitational twitch of the solar system may have been a disturbance in the asteroid belt between Jupiter and Mars, creating the Late Heavy Bombardment that showered Earth with meteorites some 4 billion years ago, 500 to 600 million years after the sun formed. Since then, however, the objects that constitute our solar system have settled into a tranquil, if sensitive, balance – to our own inestimable advantage. Richard Webb



Where do comets come from?

Few cosmic apparitions have inspired such awe and fear as comets. The particularly eye-catching Halley's comet, which last appeared in the inner solar system in 1986, pops up in the *Talmud* as "a star which appears once in seventy years that makes the captains of the ships err". In 1066, the comet's appearance was seen as a portent of doom before the Battle of Hastings; in 1456, Pope Callixtus III is said to have excommunicated it.

Modern science takes a more measured view. Comets such as Halley's are agglomerations of dust and ice that orbit the sun on highly elliptical paths, acquiring their spectacular tails in the headwind of charged particles streaming from the sun. We even know their source: they are Kuiper belt objects (KBOs) tugged from their regular orbits by Neptune and Uranus.

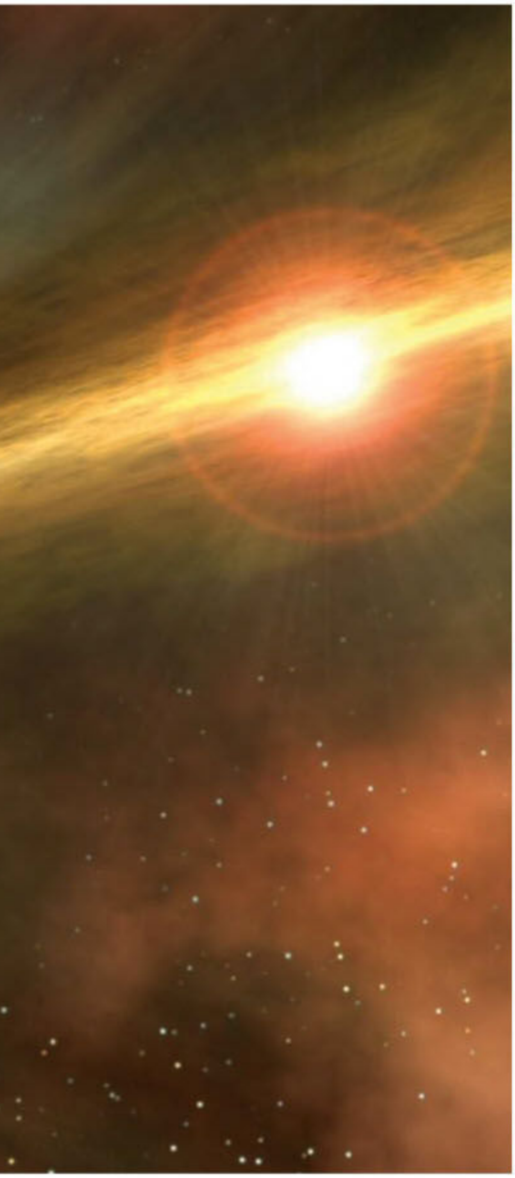
But there's a problem. Certain comets, such as Hale-Bopp, which flashed past Earth in 1997, appear simply too infrequently in our skies. Their orbits must be very long, far too long to have an origin in the Kuiper belt. The conclusion of many astronomers is that the known solar system is surrounded in all directions by a tenuous halo of icy outcasts, thrown from the sun's immediate vicinity billions of years ago by the gravity of the giant planets.

This celestial Siberia is known as the Oort cloud, after the Dutch astronomer Jan Oort, who proposed its existence in 1950. This diffuse sphere of material encircling the solar system has never been seen, but if the longest-period comets are anything to go by, it must be vast, reaching out about 1000 times further than the outer edge of the Kuiper belt. At such huge distances, it would not be passing planets that throw the comets sunwards – it would be the tug of the Milky Way and nearby stars. The Oort cloud would truly be where our solar system meets the void.

Unfortunately, spotting the Oort cloud is extremely difficult. It is simply too dim and distant, and its pieces too small, for telescopes to spy. That is unfortunate, as counting and estimating the size of such objects could help in reconstructing a picture of the sun's birthplace, and perhaps provide us with a glimpse of the unadulterated material from which the giant planets were pieced together.

So far, the only information about this primordial rubble comes from stray comets and the largest KBOs, which should have a similar composition. "That's like trying to figure out what a whale looks like from the exposed blowhole on one side and the tip of the fin on the other," says Hal Levison, a planetary scientist at the Southwest Research Institute in Boulder, Colorado.

Even so, mapping the rest of the whale might be only a few decades off. Oort cloud objects should



dim and diffract the light coming from distant stars. These occultations last just a fraction of a second, but astronomers can use them to measure the size and distance of the intervening body, a technique already being put to work on KBOs. Flickers induced by turbulence in Earth's atmosphere make the subtle detections of the more distant Oort objects impossible from ground-based detectors, but future space-telescope surveys should be able to detect them in great numbers.

Other mysteries remain. The numbers and trajectories of the long-period comets seen so far suggest that the Oort cloud contains trillions of objects a kilometre across or larger, with a combined mass several times that of Earth. That is more material than our current ideas about the solar system's formation can explain – which means that our models might need a fundamental overhaul, says Levison. Rachel Courtland

How will it all end?

We live in uninteresting times. Since the ructions that created the planets in the solar system's first 100 million years – and apart from an early migration of the giant planets and the odd colliding comet not swept safely aside by Jupiter – nothing much has really been happening. The planets circle like clockwork, the sun burns steadily, and even delicate life has survived on at least one world.

It cannot last. Something unpleasant is bound to shatter this comfortable calm.

Our sun will die, of course, about six billion years from now. But things could get ugly long before that. The steady gyrations of the solar system today may conceal the seeds of chaos. Even the tiniest of irregularities can build up over time, gradually altering the paths of the planets. Between now and final sundown, it has been calculated, there is a roughly 2 per cent chance of catastrophe. Mars might drift too close to Jupiter and be thrown out of the solar system. If we're very unlucky, hot-headed Mercury could run wild and smash into Earth.

Meanwhile, the sun will slowly get brighter. Within 2 billion years, its heat will probably kill off life on Earth's surface. Mars, on the other hand – if it is still there – should gain a cosier climate. Even if it is dead today, it could one day come to life.

But again, not forever. When the sun's core burns up the last of its hydrogen fuel, the whole structure of the star will radically rearrange. It will slowly bloat to more than a million times its present volume, becoming a red giant. That giant will swallow Mercury and Venus and, according to the latest simulations, probably Earth too.

Baked by the sky-filling sun, and stained redder than ever, Mars will now definitively be dead. The icy moons of Saturn and Jupiter might in turn become hospitable. Saturn's giant moon Titan is particularly promising, as it already holds a rich soup of organic molecules. The red giant's heat could leave once-icy Titan with a global bath of water and ammonia where those organic molecules could form life.

Any creatures that bob to the surface of these outer moons would look up at a rather different sky to the one we have come to recognise. By that time, the Milky Way will probably have collided with our neighbouring galaxy Andromeda to form a unified "Milkomeda", where violent bursts of star formation – the nurseries of a new generation of solar systems – will light up the heavens for a time.

Any late flowering of life in our solar system, if it happens at all, will not last long. After its brief escapade as a red giant, the sun's inner furnace will finally fail, and it will cast off its outer layers and shrink into a tiny white dwarf. The briefly balmy Titan will freeze over once more. Its host planet Saturn, together with the other denizens of the outer solar system, will continue on their lonely orbits for tens of billions of years more, until treachery from within or marauders from without do for them, too. Jupiter or Saturn could eject their lighter comrades, Uranus and Neptune, or passing stars could strip away any planet, even massive Jupiter.

The future is never certain, though, and alternative endings can be written. There is a slim chance that the whole solar system, sun and all, might be thrown out of Milkomeda intact. Out in the emptiness of intergalactic space, the planets would be safe from marauders. There they could continue to circle our darkening star until their energy is eventually sapped and they spiral inwards. One by one as they hit the black-dwarf sun, a few final flares will rage against the dying of the light. Stephen Battersby ■

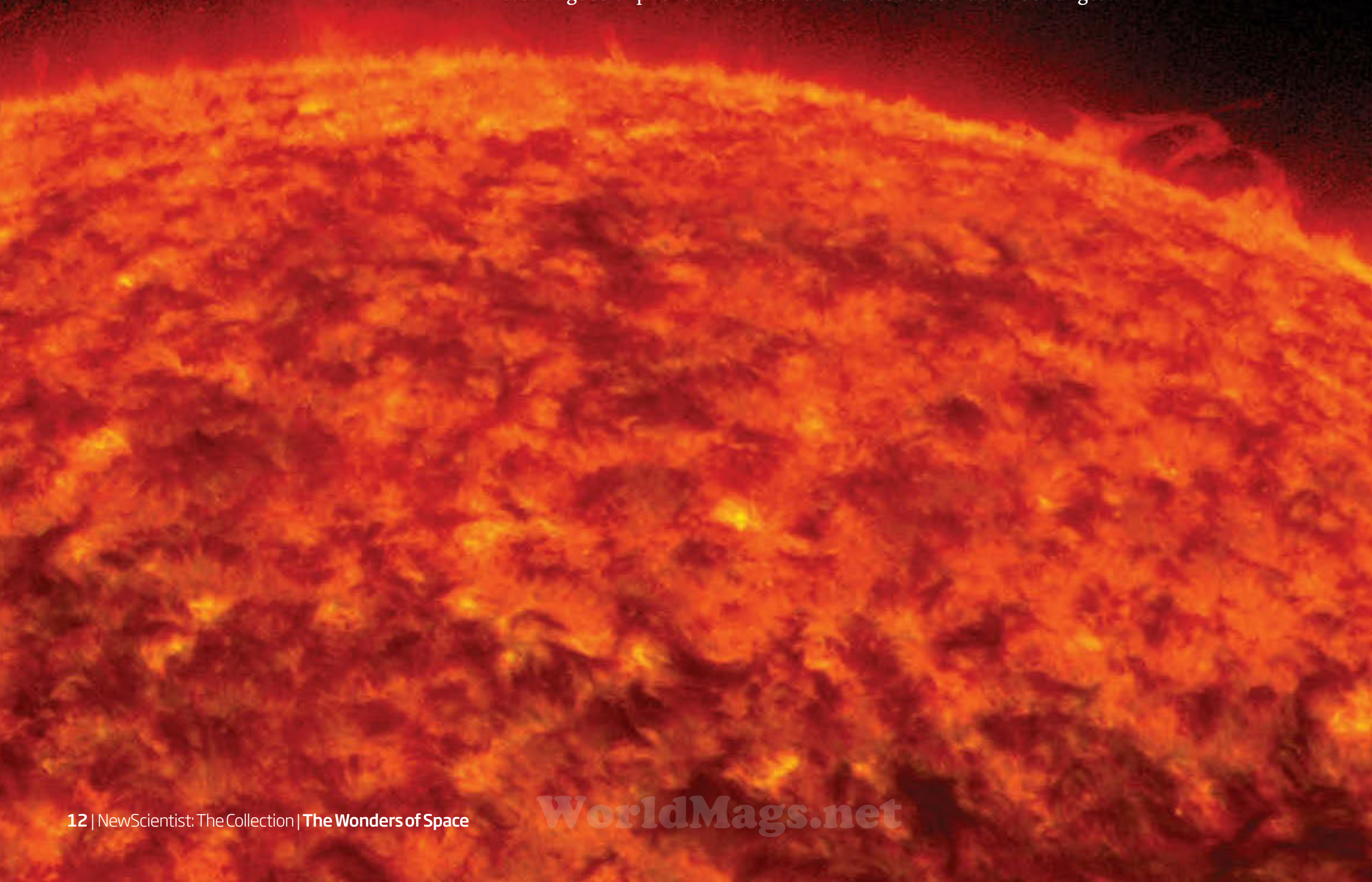
Strangest star

We look to the stars to understand the universe, but even our own sun holds plenty of surprises, finds **Rebecca Boyle**

BILLIONS and billions of stars fill our galaxy. Many burn bright, destined to become supernovae, while others are dim burnouts. They come alone and in pairs; with or without planetary companions. We have searched the far reaches of the universe in the hope of understanding the stars, but ultimately everything we know is based on our sole reference point, the sun. Yet our home star remains plenty mysterious.

"It's expected that it's understood, because it's right there, it's so close and dominant in the sky," says astrophysicist Eamon Scullion from Trinity College, Dublin, Ireland. "How are we going to understand any other aspect of space if we can't get to grips with the nearest star?"

While we may have to go back to square one, there are things we do know about our sun. It is made of plasma – gas that has been ionised, or highly charged. It fuses hydrogen in its core. It blasts us with radiation and, crucially, its life-giving light. As stars go, it is roughly middle-aged, having been around for 4.6 billion years. And it probably has 5 or so billion more to go before it swells into a red giant that consumes Mercury, Venus and Earth. Yet strange solar phenomena abound and here are some of the strangest.



It rains on the sun

We know the sun affects weather on Earth and in space, but it has its own dramatic weather phenomena, too.

"People have this image of a giant ball of gas that's on fire, and everything is streaming away from it at thousands of kilometres per second," says Scullion. In fact, the sun's plasma can fall back to the surface as rain.

Though this so-called coronal rain was predicted about 40 years ago, we couldn't see or study it until our telescopes became powerful enough to spot it happening. It works a bit like the water cycle on Earth – where vapour warms, rises, forms clouds, cools enough to condense into a liquid and falls back to the ground as precipitation. The big difference is that the plasma doesn't change from gas to liquid, it simply cools enough to fall back down to the solar surface.

This all happens very quickly and on a gargantuan scale, with "droplets" the size of countries plunging from heights of 63,000 kilometres – about one-sixth the distance from Earth to the moon. "You basically generate something the size of Ireland in 10 minutes, and drop it out of the sky at a rate of 200,000 kilometres an hour," Scullion says.

Solar tornadoes also form in a familiar fashion. Swirling solar plasma creates a vortex, which causes magnetic fields to twist and spiral around into a super-tornado that reaches from the surface into the upper atmosphere. Here they transfer energy and help to heat it, or so scientists believe.

It has long-lost siblings

The sun may be on its lonesome now – its closest neighbour is 4.2 light years away – but that wasn't always the case. Once upon a time it had close family. After their birth in the same cloud of dust and gas that formed our solar system, these solar siblings scattered hundreds of light years apart in the Milky Way. In May 2014, astronomers reported the first one: a star called HD 162826.

"It looks like the sun, but a little bit bluer," says Ivan Ramirez at the University of Texas at Austin, who led the study. It's also warmer than the sun and 15 per cent more massive. The star is about 110 light years away, and you can see it with the aid of a pair of binoculars in the left arm of the constellation Hercules.

To find its family ties, Ramirez's team combed through galactic archaeology studies, which model the motions of the Milky Way. These predictions laid out where sibling stars would be now if they had formed in the same place as the sun. Though they spread out in different directions, their positions still give away their birthplace, Ramirez says.

He narrowed down the search area to 30 stars, and then looked at them closely to find a family resemblance. Only HD 162826 had a similar chemical make-up to the sun. A separate team led by Eric Mamajek at the University of Rochester in New York also studied the star and found it is the same age as the sun, as would be expected for two stars born together. Even more tantalising, HD 162826 is already in a catalogue of stars that might harbour planets.

Locating solar siblings could tell astronomers more about the birth of our solar system, such as what conditions were like when the sun and planets formed (see "The sun's siblings", page 82). But beyond scientific curiosity, Ramirez just wanted to find a member of the sun's nuclear family. "It's a cool thing to do," he says.

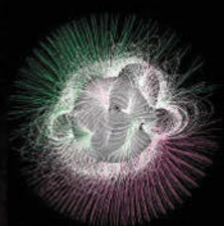
LEFT: NASA/GODDARD SPACE FLIGHT CENTER/SDO; RIGHT: NASA/GODDARD SPACE FLIGHT CENTER

He plans to keep looking for more of our sun's lost littermates. Most are probably red dwarf stars, which are the most common stars in the galaxy. They are smaller and cooler than the sun, so they are much harder to find. But the Gaia telescope, launched in 2013, may help locate more solar siblings as it will observe a billion stars to make the first 3D map of the Milky Way.

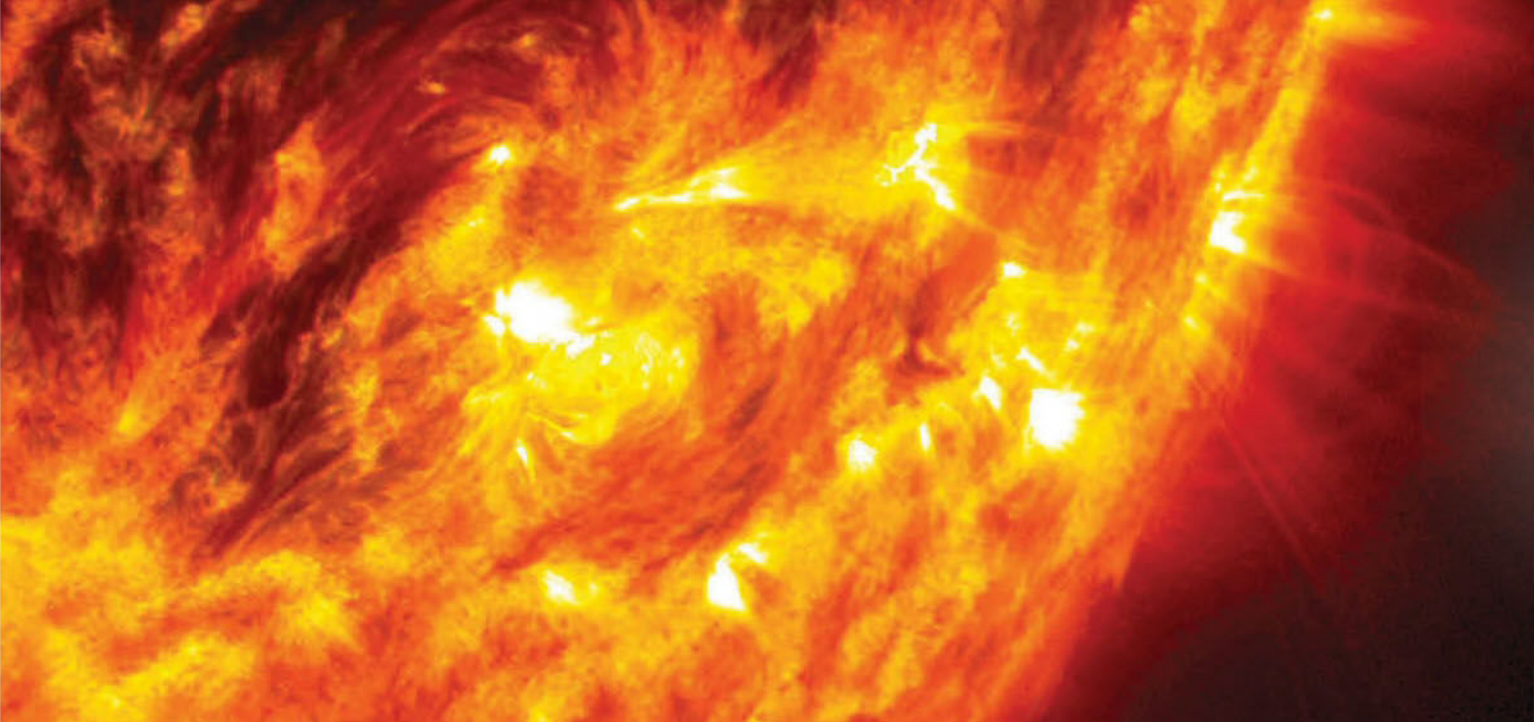
It has a freaky calendar

Our planet's calendar is well known: it takes 24 hours to spin once on its axis – a day – and 365 days to travel around the sun – a year. Yet the sun's schedule is nothing like ours. Different parts of the sun spin at different rates. So while a day at the equator lasts 25 days, regions close to the poles take a few days longer to make a complete rotation. This uneven spin leads to distortion in the sun's magnetic field, which has knock-on effects. As the equator spins, it drags the magnetic field that connects the sun's poles, says Alex Young at NASA's Goddard Space Flight Center in Greenbelt, Maryland. This results in another strange calendar phenomenon: solar maxima and minima.

As the sun's magnetic field gets wound up by the spin "it starts to build tension and pressure, much like when you twist a rubber band and it knots up", Young says. Something has to give, so the magnetic fields snap and release energy in the form of heat, either as solar flares or furious clouds of energy called coronal mass ejections (CMEs). ›



The sun's magnetic field reverses every 11 years or so



This cycle, from magnetic twisting to energy releasing, happens over roughly 11 Earth years – giving the sun its own calendar. During what's called a solar minimum, flares are few and so are dark patches called sunspots that appear on the sun's surface due to intense magnetic fields.

In solar maxima, more sunspots burst over the surface where they spew more flares and CMEs. Torrents of charged particles also stream through gaps in the sun's atmosphere and across the entire solar system. This can affect us, causing blackouts on Earth and damaging satellites. But each solar cycle varies, and we don't understand why, which makes them and their effects unpredictable.

The current cycle is unusually calm and has been one of the weakest since records began in 1755. This is in spite of some major solar storms, together with a colossal solar flare in 2012, which would have packed some punch had it hit Earth.

Predictions just a couple of years ago suggested this cycle would be a scorcher, which shows just how little we understand solar cycles, says Todd Hoeksema, a solar physicist at Stanford University in California. "It's like predicting the stock market. Past performance is no guarantee," he says.

Also roughly every eleven years, the sun undergoes yet another calendar change: its magnetic field reverses. North becomes south, and vice versa. Earth does this, too, but only every 300,000 years or so (we are long overdue one). The sun's polarity last reversed in 2013, though the flip took scientists many months of analysis to confirm.

"Why is it 11 and 22 years and not 15 and 30? We don't know the answer to that yet," Young says. "When you think about it, it's such a short amount of time, given that the sun has been around for 4.6 billion years."

It breathes

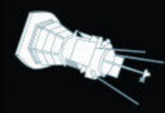
As the sun follows its 11-year solar cycle, it changes, altering its output of solar wind, X-rays, ultraviolet and visible light. This has the knock-on effect of changing the size of the huge magnetic bubble of charged particles, called the heliosphere, that the sun blows around itself to way out beyond Pluto.

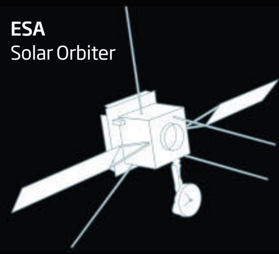
These changes affect everything from Earth's climate to the Voyager 1 spacecraft, which finally entered interstellar space in 2013.

The sun provides nearly all the energy that drives Earth's climate – 2500 times as much as all other sources combined, according to Greg Kopp, a solar physicist at the University of Colorado's Laboratory for Atmospheric and Space Physics. In past epochs, solar cycles were partly responsible for warm periods and mini ice ages. Low solar activity drives cold winters in northern Europe and the US, and mild winters over southern Europe – although global warming means globally averaged temperatures are on the rise.

We now understand what's going on a little better thanks to a space-borne instrument called TIM, launched by NASA in 2003. TIM keeps tabs on the spectrum of energy the sun emits, and detects subtle changes in energy output so scientists can distinguish between human causes of climate change and purely natural causes we can't control.

Changes in the sun's output affect much more than just our climate, however. During a solar minimum, the solar wind streams from the poles at a much faster speed, so there's more pressure pushing against material from interstellar space. During solar maxima, the





	NASA Solar Probe Plus	ESA Solar Orbiter
Closest orbit	6 million km	45 million km
Launch date	July 2018	October 2018
Mission duration	7 years	7 years

sun's magnetic fields are more knotted up and not as much wind escapes, so the heliosphere contracts. "There's sort of an 11-year breathing," says Hoeksema.

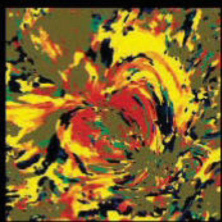
The solar wind has been 20 to 40 per cent weaker than expected this cycle, he says. This shallower breath is one reason why Voyager 1 left the heliosphere earlier than scientists expected.

It defies thermodynamics

Solar tornadoes are bizarre enough on their own, but they might help explain one of the sun's weirdest characteristics: its atmosphere is hotter than its surface. At 5700 kelvin the sun's surface is scarcely cold, but it is frigid compared to the corona. The highest part of the sun's atmosphere, more than 1 million kilometres above the surface, can reach temperatures of several million kelvin.

Generally, an object cools as it moves away from a heat source; a marshmallow will toast faster when it's closer to a campfire flame than further away. But the sun's atmosphere does the opposite. Energy must be flowing into the corona, heating it up – but no one knows where this energy comes from. "We don't fully understand the physics of what's going on," Scullion says.

Computer visualisations might paint a clearer picture of this process – and quite artistically, too. In one simulation, NASA Goddard astrophysicist Nicholeen Viall added colour to data coming in from NASA's Solar Dynamics Observatory (SDO), which observed the sun's coronal plasma in 10 different wavelengths that each correspond to a temperature. The result is a swirling movie reminiscent of a Van Gogh painting. But Viall's visualisation suggested the atmospheric plasma was cooling, not heating. This may be



Solar atmosphere: glowing like a Van Gogh painting

because the heating is happening faster than SDO can detect.

Much of the energy that heats the corona appears to come from the so-called transition region – the area between the sun's corona and the next atmospheric layer down. Tornadoes, rain, magnetic braids, plasma jets and strange phenomena called "spicules" are all thought to play a role in this heating process, bringing energy from the lower regions of the sun and depositing it higher up. But no one knows exactly how. NASA's Interface Region Imaging Spectrograph mission has been observing this region since 2013, and physicists like Scullion try to simulate these energy exchanges using models in the hope that they will yield clues that scientists can look for on the real thing.

It's hard to get there

To truly understand all these solar conundrums, we need to get as close to the sun as possible. That's not as simple as flying straight there, as the operators of two new spacecraft that will fly closer to the sun than ever before are finding.

Solar Orbiter is a European Space Agency mission launching in 2018, aiming to fly within 45 million kilometres of the sun. It will photograph the sun's poles for the first time, which should help scientists understand how the sun generates its magnetic field, and may even give insights into why its magnetic polarity flips so frequently.

By getting a close-up view, the probe will also be able to sniff the pristine solar wind, before it has reached Earth. The main goal is understanding how the sun interacts with the environment around it, says Tim Horbury, a physicist at Imperial College London and the principal investigator on the Solar Orbiter's magnetometer. "The basic physics is understood, but a lot of the detail is not," he says.

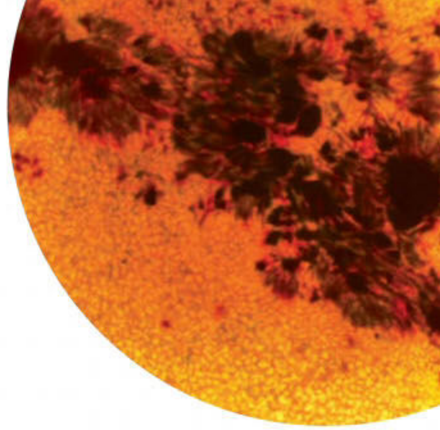
NASA's Solar Probe Plus mission is set to launch shortly before the ESA's mission and come even closer, just 6 million kilometres from the sun's surface. To get there, it will approach in a looping, circuitous route, like a matador approaching a wary bull. The slow approach is partly for safety's sake: as the probe gets closer, scientists can carefully monitor any threats from radiation or heat and adjust the approach if anything goes awry.

Solar Probe Plus will lap round Venus seven times to put it on the right trajectory and also to build up speed and momentum to slingshot closer to the sun – at its closest approach, it'll zip past the sun at 200 kilometres per second.

Shielding a spacecraft from solar radiation is one of the most important jobs in spaceflight, but it's even harder when you are sidling up to the source. The technology to do it hasn't existed until now, Horbury says. Both craft will have beefy heat shields to protect their sensitive instruments from searing temperatures.

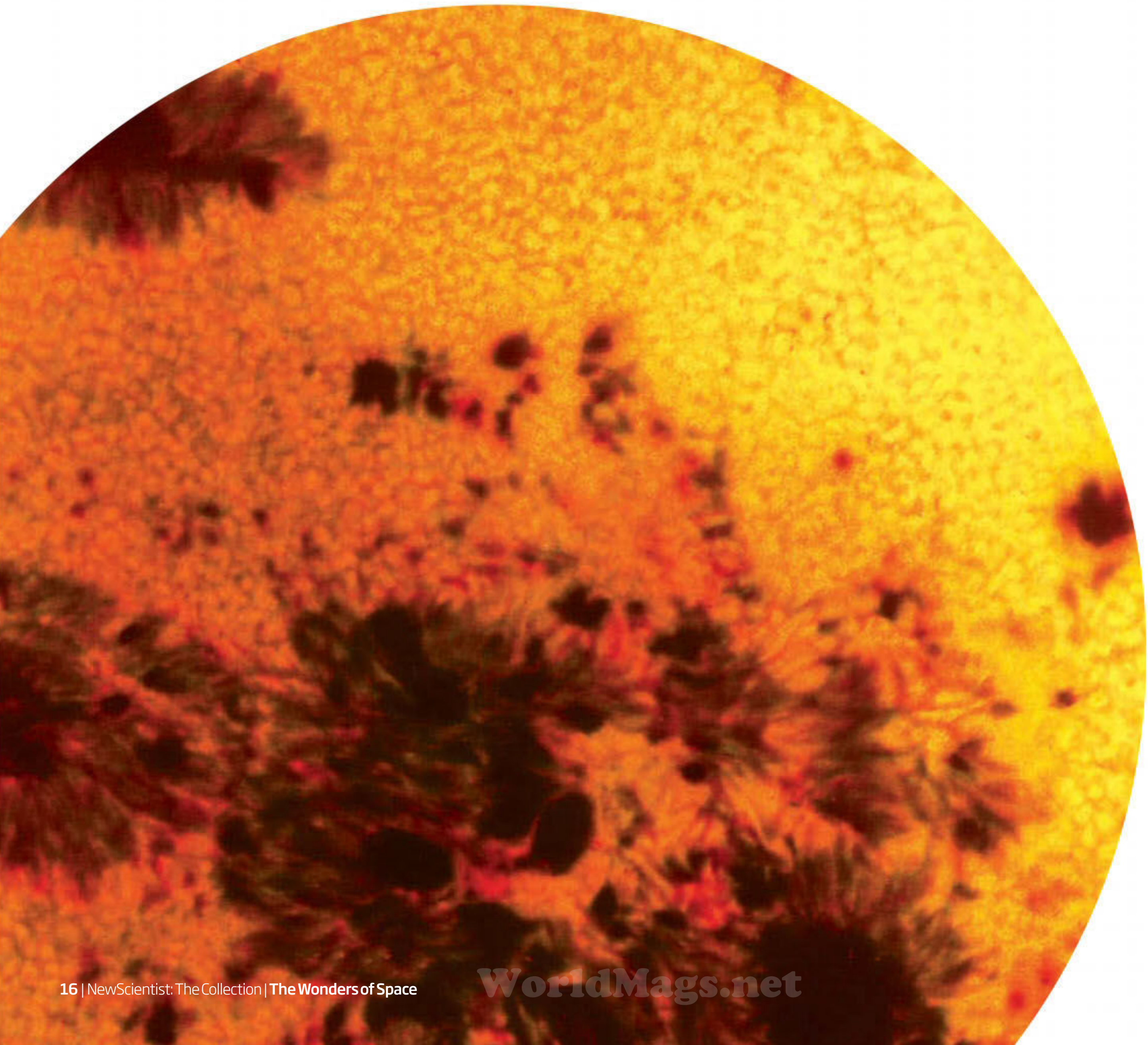
Both spacecraft will try to answer questions, including how the atmosphere is heated and how the sun generates its wind. But they will still be far from answering everything there is to know about our star, says Young. "The problem is that you don't know what you don't know," he says. ■

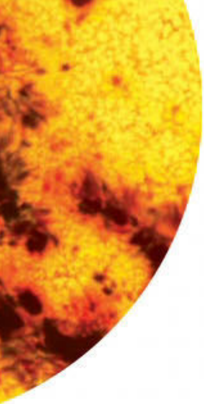
LEFT: NASA/GODDARD SPACE FLIGHT CENTER; RIGHT: NASA/SDO



The tally of splotches on our sun tells us what it's up to. Good thing we now agree on how to count them, says Brian Owens

Spot of bother





FOR years, Gustav Holmberg would leave his desk at Lund University in Sweden to take part in a scientific ritual stretching back to Galileo's time.

Back at his flat, the historian of science would set up a modest telescope and, taking due care not to burn his eyes, point it directly at the sun. He would spend 5 minutes or so counting, and then upload a number to a server in Belgium, to be combined with similar numbers from observers around the globe, many of them amateurs like himself.

This number, updated daily, allows satellite engineers to predict how the sun's future activity will affect their spacecraft. Climate scientists use it to pick out the sun's long-term effects on Earth's climate. Electricity companies use it to anticipate solar storms that could affect their grids. It is the international sunspot number: the world's oldest continuous data series, and one of its most important. "It is probably, apart from the Dow Jones index, the most used time series ever," says Leif Svalgaard, a solar physicist at Stanford University in California.

But there is a problem. There is not one sunspot number, but two.

In the past couple of decades, a rival series has revealed the existence of mysterious blemishes in the official sunspot record that cast doubt on its accuracy. That is embarrassing for the scientists involved and problematic for those who rely on the record's accuracy. What to do?

Sunspots are dark splotches that mark cooler patches on the solar surface. They correlate with areas of intense magnetic activity that are breeding grounds for violent outbursts of matter and radiation from our star. If it weren't for the protective hull of Earth's atmosphere and magnetic field, these solar flares and coronal mass ejections would rapidly fry life on our planet.

Observers peering through the first telescopes in the early 1600s were blissfully unaware of all this when they started to systematically record dark spots on the solar surface. Many at the time rejected the idea that God's celestial orb could be anything less than perfect, and assumed these passing blotches must be shadows of other bodies orbiting the sun. It was Galileo who championed the view that they were features on the sun itself.

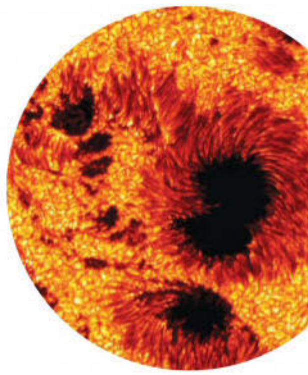
In the 1840s, the Swiss astronomer Rudolf Wolf took observations of sunspots to a new level. He diligently recorded his own measurements each day, and delved into the piecemeal records of earlier astronomers to extend the series of observations back to 1700. In the years before that, the sun was going through a prolonged period of unusually low activity known today as the Maunder minimum, and Wolf felt there were too few reliable records to look further back.

Counting sunspots is not as easy as it sounds. Sunspots tend to cluster together in groups, and individual spots within a group can be difficult to discern. To take account of these uncountable spots, Wolf came up with a formula to calculate the "relative sunspot number", which he defined as 10 times the number of sunspot groups, plus the number of clearly distinguishable individual spots. Since different observers with different telescopes tended to count slightly different numbers of sunspots, Wolf used overlapping periods to assign correction factors to the numbers from each new observer, and so ensure these numbers were consistent with his own.

This same system was used for over a century by Wolf and his successors in Zurich, with each new observer's results calibrated to an existing reference standard. When the Zurich observatory closed in 1981, the Solar Influences Data Analysis Center (SIDC), based at the Royal Observatory of Belgium in Brussels, took responsibility for compiling the number, known also as the Wolf number in honour of its founder. Since 1951, the US National Oceanic and Atmospheric Administration (NOAA) based in Boulder, Colorado, has compiled a second series using Wolf's formula, using data from different observers, that produces results broadly in agreement.

Both these sunspot series show consistent features over centuries. The sun's activity varies over a roughly 11-year period, rising to a maximum before dropping off again to almost nothing. We're not altogether sure about the cause, but maximum activity always occurs just before a regular flip in the polarity of the sun's magnetic field; the last such flip occurred just a few years ago (see "Strangest star", page 12). Not all peaks and troughs are equal. There are extended periods of low activity, such as the Maunder minimum, as well as prolonged periods of high activity. Some solar physicists think we may be entering a long quiet period now.

But how sure can we be? In the 1980s, nearly 100 years after Wolf's death, the seemingly model historical continuity of the sunspot series was seriously called into question. Douglas Hoyt, a solar physicist then working at a company called Research and Data ›



Eye of the beholder: sunspot counting is open to interpretation

L-R: JACK NEWTON; NOAO/SPL; SCHARMER ET AL, ROYAL SWEDISH ACADEMY OF SCIENCES/SPL

Systems in Greenbelt, Maryland, noticed that the English astronomer William Herschel had recorded sunspot observations over periods in the early 1800s when Wolf's record implied none had been made. Hoyt concluded that Wolf may have missed records kept in English, and possibly others. Along with Ken Schatten of the NASA Goddard Space Flight Center, also in Greenbelt, he began trawling through museums, libraries and observatory archives around the world, gathering as many historical sunspot observations as he could. In the end, the two dug up about 100,000 observations that Wolf had not used. Many were recorded during the Maunder minimum, extending the series all the way back to Galileo in 1610. "Even so," says Hoyt, "I probably missed some observations myself."

Rival series

These earlier observations counted only groups of sunspots, so the new series, ending in 1995, was directly comparable with that based on Wolf's method only after careful cross-checking and calibration. That turned up a surprise. Although the two series agreed fairly well in some places, in others they differed radically. In some periods before 1885, the new group sunspot number was lower than Wolf's by as much as a half (see diagram, below). Between 1945 and 1995, the Wolf numbers near maximum were consistently higher than the numbers revealed by the group method.

This is a problem. To take one example, the level of solar activity controls the rate at which particles evaporate from the uppermost layers of Earth's atmosphere. These particles exert a tiny, but perceptible drag on spacecraft in low Earth orbit such as the International Space Station. Predictions of solar activity based on sunspots are used to determine what orbit a satellite should be put into, how much fuel it will need, and how long the mission might last – as well as how much it will cost to insure it against loss in a solar storm. The US Air Force has newer Wolf numbers hard-coded into the operational programmes that control its rockets and satellites.

But it is in climate science where the existence of two rival sets of sunspot data has caused the most controversy. By grafting Hoyt and Schatten's series on to longer-term data inferred from tree rings and ice cores, it is possible to argue that solar activity has been steadily increasing, and indeed is higher today than at any time in the past 8000 years. That, rather than our own greenhouse-gas emissions, is the reason why the planet is warming, the argument goes.

For Svalgaard, this is a deeply unsatisfactory situation. "Why can't we provide a number that we can have some confidence in?" he asks. "That is something we as solar physicists should be ashamed of."

A few years back, he decided to do something about it. He wanted to get to the bottom of what was causing the inconsistencies and come up with a single, vetted number that everyone could agree on. He and his colleagues think they are now just about there.

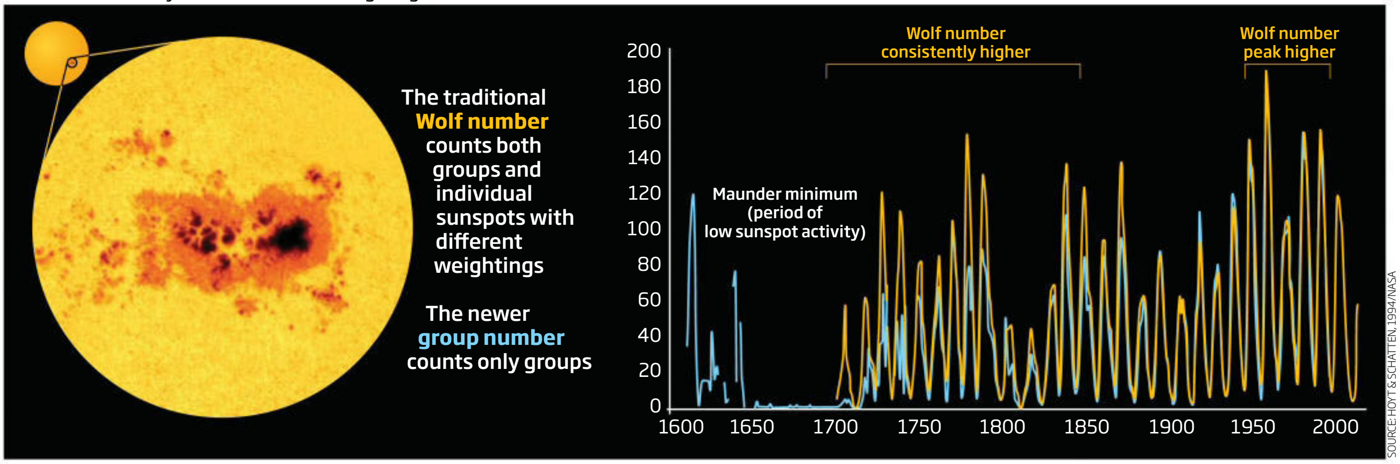
The issue of the jump in Wolf's number in 1945 was a strange one. Daily variations in the magnetic field observed at Earth's surface are also influenced by solar activity, and Svalgaard noticed that these did not match up with the sunspot numbers as well as they should have after 1945. Something had gone awry with the counts. It turned out that, sometime after taking over the Zurich observatory in the mid-1940s, its director Max Waldmeier changed the way the sunspots were counted. Because it had become clear that bigger spots represented increased magnetic activity, he decided to give them a greater weight. While the smallest ones counted as just one spot, he counted larger ones as many as five times – only he told hardly anyone about it.

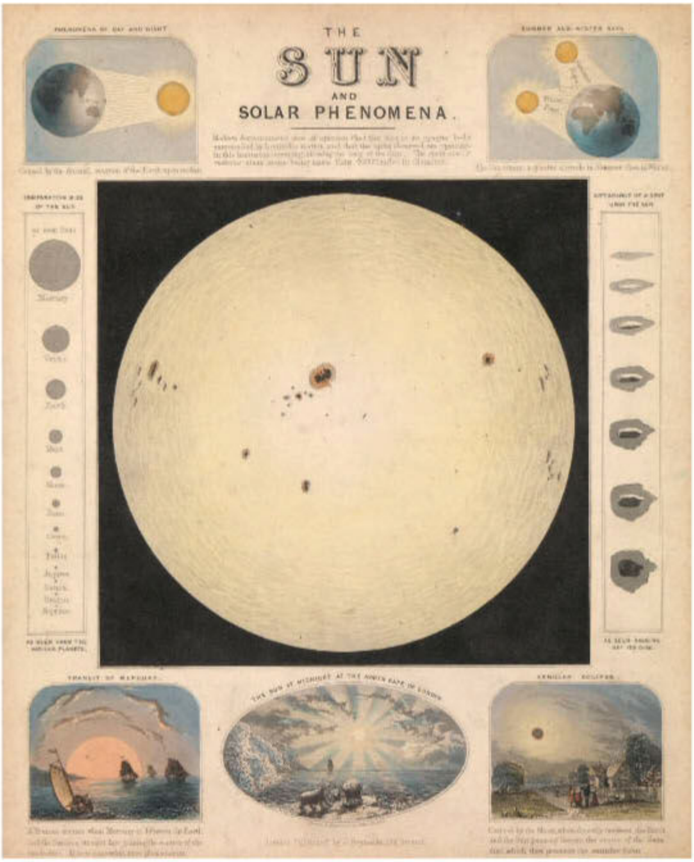
One of the few he did tell was Sergio Cortesi at the Specola Solare Ticinese, a small observatory near Locarno in the south of Switzerland that was set up as a twin station to Zurich. Cortesi is still there counting sunspots. After the closure of the Zurich observatory, Locarno became the reference station for the sunspot series, and every new observer's count was referenced to Cortesi's counts, which in turn were calibrated to Waldmeier's. Cortesi had assumed Waldmeier's recalibration was

"In the mid-1940s, the director of the Zurich observatory changed the way sunspots were counted – only he didn't tell anyone"

Spot the difference

It can be difficult to pick out individual spots on the sun's surface. The two main methods for calculating sunspot numbers have produced results that in some cases differ radically, even after careful weighting and calibration





Sunspots have long captivated popular imagination

JAMES REYNOLDS; JOHN EMSLIE/NATIONAL MARITIME MUSEUM, GREENWICH, LONDON

common knowledge, so the blip Waldmeier introduced went uncorrected. The result is that, starting around 1946, the Wolf numbers are about 20 per cent too high.

Given the places where these numbers are hard-coded, they can't simply be changed. Because the aim is to ensure the consistency of the series over time, rather than establish an absolute number, Svalgaard's proposal, hammered out with colleagues from the US Air Force Research Laboratory and SIDC among others, is to bump up all the older, pre-1946 numbers by 20 per cent.

The divergent numbers before 1885 were trickier. In compiling the earlier parts of their data series, Hoyt and Schatten had faced the same problem as Wolf: how do you compare sunspot counts from different observers, with different eyesight, different telescopes, and even perhaps different opinions on what constitutes a group of sunspots in the first place?

They had handled this in much the same way that Wolf did: by stringing together a daisy chain of overlapping observers, correcting the numbers up or down so that they produced the same average number of sunspots in the time periods when two observers overlapped. The problem with this approach is that if any one particular number is way off-beam, errors will propagate through the series and accumulate. "It's like the children's game Chinese whispers," says Svalgaard.

Two such errors in particular came to light. The first was in sunspot records kept by the Royal Observatory in Greenwich, UK, from 1874 to 1974. Hoyt and Schatten had used this long-running series to calibrate other observers' data, but comparison with more than 20 other contemporary observers reveals that in its first 20 years the Greenwich series was drifting. Equal sunspot counts do not necessarily represent the same level of solar activity throughout the record.

The second error was in the final multiplier Hoyt and Schatten used to ensure their average sunspot count matched Wolf's. Soon after starting the sunspot series, Wolf became chairman of the Swiss geodetic survey and then director of its weather service. From the 1860s until his death in 1893 he was almost constantly travelling, and continued with his observations not with his large telescope in Zurich, but with a smaller, portable one with which he saw on average 40 per cent fewer sunspot groups. Although Wolf adjusted his own counts to keep the Zurich number constant, Hoyt and Schatten had calibrated to his raw counts.

The upshot is that Hoyt and Schatten's sunspot numbers before 1885 needed to be revised upwards, to bring them into line with the Wolf number and ensure the reliability of the series. And as of last July, the recalibrated figures were officially adopted by the SIDC.

Schatten gave the proposal his blessing, despite the fact it has highlighted flaws in his work. "Of course, one doesn't like it when the work one does is not perfect," he says, but he thinks the outcome is the right one. A more accurate time series will allow for a better understanding of past solar cycles. "And the past is the key to the present, and the future," says Svalgaard.

Climate controversy

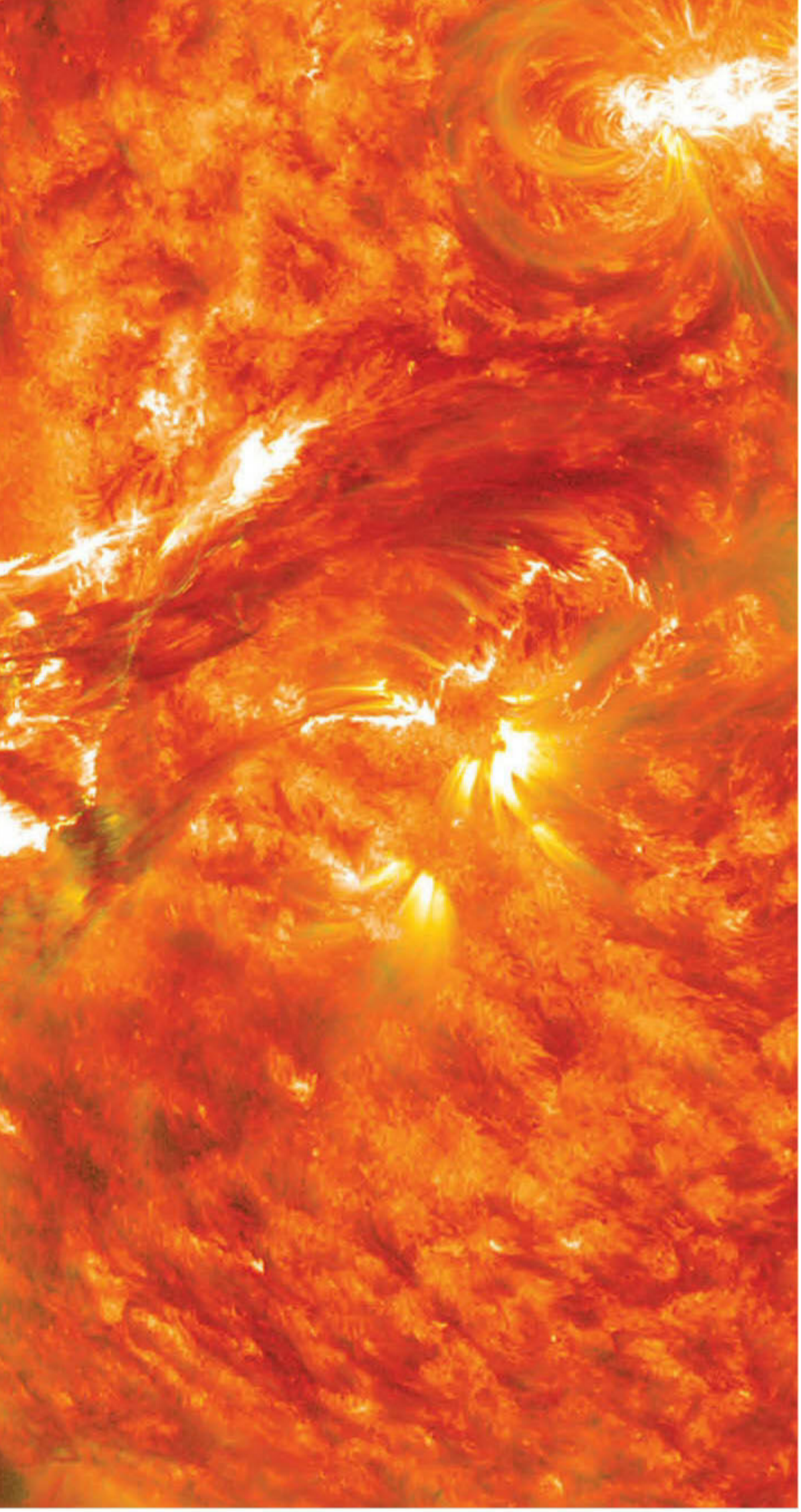
Clearing up its blemishes could give the sunspot record new life, says P. T. Jayachandran, an atmospheric physicist at the University of New Brunswick in Canada. Satellite engineers had been moving away from using sunspot numbers to calculate solar activity, in part because the measurements were considered too unreliable. Instead, they had begun to use direct measurements of solar flux, the radio emissions from the sun. But those flux observations only go back as far as the 1940s. For any view of patterns of solar activity stretching further back in time, these records too had to be calibrated to the sunspot records.

This problem becomes especially acute when it comes to how the sun's activity affects Earth's climate. This becomes more uncertain over longer time periods, says Joanna Haigh, a climate physicist at Imperial College London, partly because there have been "extreme differences in assumptions" about the power output from the sun. With Svalgaard's corrections to the revised sunspot series, it no longer seems that the sun is going through an unusually active phase. In fact, it has been mostly stable for the past few centuries since the Maunder minimum. The argument that the sun, and not human activity, is driving global warming loses one of its supports. Svalgaard is still not so naive as to think this will be the end of the argument. "We expect a grand fight on that front," he says.

With the wrinkles in the earlier data ironed out, we can have a little more confidence in the world's oldest data series. And while plans are afoot to automate the collection of the international sunspot number, for all their imperfections humans remain the most reliable observers. Which is why Holmberg plans to continue delivering his numbers as he always has – methodically, consistently, without fail. As a scientist and a historian, he's proud his hobby can continue to be put to scientific use. "It gives me satisfaction that my data become part of something bigger." ■

Star burst

Tracking down the cause of a radiation blast that hit Earth in medieval times has led us frighteningly close to home, finds Stuart Clark



NASA/GSFC/SDO/REX FEATURES

Distance is no protection when the sun is in a rage

SOMETHING with almost unimaginable power hit Earth in AD 775. Europe was in the grip of the dark ages, yet the skies were alight. "Fiery and fearful signs were seen in the heavens after sunset; and serpents appeared in Sussex, as if they were sprung out of the ground, to the astonishment of all," recorded the 13th-century English chronicler Roger of Wendover.

We don't just have his word for it. Over the past few years, new evidence has come to light confirming that something cataclysmic took place in the solar system that year. But what? There are no signs of a mass extinction or an environmental disaster which would normally accompany such an event. More mysterious is that no trace of it appears in the sky today.

The only clues to what happened are found locked inside ancient tree rings. What they reveal is shocking. A supremely powerful blast of radiation struck our atmosphere out of the blue, changing its composition for millennia. While the medieval world emerged unscathed, we wouldn't be so lucky today. Our technology-reliant society would be devastated by such an event: satellites would fry, power stations would melt, and we would be without communications and power for years. We might never bounce back.

This makes identifying the source of the blast a priority. While various perpetrators have been proposed, we are now closing in on an answer. And the culprit, it seems, is alarmingly close to home.

With no technology to damage, the effects on the medieval world were slight. We would have missed them completely had it not been for Fusa Miyake of Nagoya University in Japan and her colleagues. They were searching for evidence of large, ancient radiation storms in tree rings from two long-lived Japanese cedar trees. In particular, they were looking for raised levels of carbon-14, a radioactive isotope that is created when energetic particles from space strike Earth's atmosphere.

Archaeologists use carbon-14 to date organic artefacts because all living things absorb carbon. Trees are particularly good at recording any variations because they only grow for a few months of the year in many climates, so you can pinpoint the amount of carbon-14 in the air at a specific time.

What Miyake found was a startling spike in carbon-14 levels around the year AD 775. In other words, a radiation storm – and a big one at that. Nevertheless, a single detection is not definitive. To truly believe the discovery, a corroborating measurement was needed from somewhere else in the world. ›

> *"Were a gigantic superflare to occur on the sun, it would destroy Earth's ozone layer and lead to mass extinction"*

"We saw Miyake's paper and became interested in measuring the effect ourselves," says Ilya Usoskin, a physicist at the University of Oulu, Finland. His team turned to ancient German oak trees that once grew near the river Main. The measurement was clear. "We precisely confirmed the results," he says. "Whatever it was in AD 775, it was a global phenomenon, and that points to an extraterrestrial source." So what was it?

Miyake's team calculated the energy needed to produce such enhanced levels of carbon-14. Her estimates for the energy were colossal – so large, in fact, that only exploding stars could provide the necessary deluge of particles. The problem is, no known supernova remnant is close enough to Earth to match the correct age. Nor are there any nearby dust clouds that could hide a remnant from our gaze.

"It wasn't a supernova," says Usoskin firmly. Instead, he and others cast a wary eye towards the sun. Reasoning that a solar flare would have produced auroras on Earth, he went looking for evidence in the historical record.

Although there were no systematic observations of the night sky in the medieval world, people watched the sky for signs that could be interpreted religiously. Usoskin uncovered Roger of Wendover's account of fiery and fearful signs and serpents in the *Anglo-Saxon Chronicle*. Fiery and fearful sounds a lot like auroras. And although it is tempting to dismiss the reference to serpents as apocalyptic embroidery, Usoskin believes this points to the sinuous way that auroras move across the sky. "Anyone who has seen auroras knows that they look like serpents," he says.

But there was no way to square the idea of a solar flare with Miyake's energy estimate, which was at least 1000 times too large.

Nevertheless, another researcher was looking suspiciously at the sun. Adrian Melott at the University of Kansas read Miyake's paper and thought that something looked wrong. In calculating the energy of the solar flare needed to produce the radiation storm on Earth, Miyake had assumed the particles were flung from the sun equally in all directions. On the contrary, said Melott, particle eruptions from the sun are fairly well directed into space, like a geyser shooting from the ground.

Correcting this assumption dropped the necessary energy by one-hundredth. "At that energy output, the radiation storm is more likely to have its explanation in the sun," says Melott.

Kamikaze comets

No one should think that this makes the cataclysm any less impressive. It is at least 20 times bigger than the biggest solar storm ever recorded, by English astronomer Richard Carrington in 1859. "We can absolutely say that what happened then was bigger than Carrington," says Usoskin. It is also 100 times bigger than any flare in the last century, according to David Eichler, a physicist from Ben-Gurion University of the Negev in Israel.

As for whether the sun is capable of behaving like that, Eichler thinks it is, but "only with a bit of help." He proposes that a comet collided with the sun and the resultant explosion provided so much energy that it drove a super solar flare. In his view, the power of the explosion came from the momentum of the comet. By the time the mountain of ice and rock struck the solar surface, it would have been travelling at more than 600 kilometres per second. "That's per second," emphasises Eichler, "not per hour."

Comets crash into the sun all the time. Known as sungrazers, some reach the surface, but most explode some way above it. They are so small, however, that the energy released by their destruction goes unnoticed. Eichler estimates that to spark a superflare, a comet the size of Hale-Bopp, which reappeared in the sky in 1997 and is estimated to be between 40 and 80 kilometres across, would be needed.

The largest sungrazing comet actually observed was Lovejoy, which flirted with fiery death in 2011. Drawing to within 137,000 kilometres of the sun and estimated to be 0.5 kilometres across, it was sufficiently distant and large enough to survive the roasting. Yet Eichler thinks the shock wave it created in the solar atmosphere during its high-speed fly-by triggered a measurable eruption of solar particles.

Cosmic misfortune robbed him of a direct observation because Lovejoy's closest approach took place on the sun's far side, out of direct view from Earth. Simultaneously, an eruption of solar particles was seen expanding into space behind the sun. For Eichler, this was tantalising and frustrating in equal measure. "The experts say that we can't know that the explosion was triggered by Lovejoy but the timing was impeccable," he says.

Now he is biding his time. "It is possible that at some time in the near future a sungrazing comet will produce an energetic particle event and that will teach us a great deal," he writes in a paper about it. But John Brown at the University of Glasgow, who studies the survival rates of such comets, thinks they will pose us little danger. He estimates that a comet would have to hit the sun directly to pose any risk of sparking a superflare, but he does hedge his bets a little because comets are so unpredictable. "Some break up when we don't expect them to," he adds.

Eichler estimates it is only a matter of time before a large comet does strike. "The odds of a comet hitting the sun are vastly larger than a comet striking Earth," he says, because the sun presents a bigger target.

Others think the sun is perfectly capable of sparking flares that big on its own. "You need a pretty big wallop to make carbon-14 in the atmosphere but the largest solar events can do

A magnetic wallop from the sun could turn all the lights out

NASA

PER-ANDRE HOFFMANN/AURORA

Reports of serpents in the sky in a medieval chronicle sound suspiciously like auroras

"Solar flares can spark a coronal mass ejection: a billion tonnes of the sun's atmosphere can be thrown into space"

it," says Melott. Although we have never seen the sun do it, we have seen this behaviour in other stars.

In a 2012 paper, Hiroyuki Maehara and colleagues at Kyoto University in Japan analysed 120 days of observations by the Kepler space telescope and found that out of 83,000 sun-like stars in the telescope's field of view, 148 produced a total of 365 superflares.

Although that means just 0.2 per cent of sun-like stars are superflarers, Melott cautions against complacency. "The really scary thing is that some of those flares are much greater than even the AD 775 event," he says. Some blasted 1000 times the estimated energy of the medieval flare into space. At those magnitudes, were one to occur on the sun, it wouldn't just be our technology at risk. The flux of particles would destroy Earth's ozone layer, allowing through the ultraviolet rays that cause sunburn and skin cancer. "It would lead to a mass extinction level event," says Melott.

The good news is that the truly gigantic superflares came only from stars that displayed extraordinarily large "starspots" – regions of intense magnetic fields and the source of solar flares – much larger than those seen on the sun.

Nevertheless, researchers are scouring tree-ring data for more large events. Miyake has found a second in the year AD 992. Although large by previously known standards, it was only about half the size of the flare that hit in AD 775. Usoskin too has been analysing his data. "There has been no greater event than AD 775 in the last 10,000 years," he says.

While this offers some comfort, it doesn't mean we can relax quite yet. That's because the flares can spark something much more dangerous and hard to predict: a coronal mass ejection (CME), in which a billion tonnes of the sun's atmosphere – essentially a torrent of energetic particles and magnetic fields – can be thrown into space.

Knock out

The trouble is that no two CMEs are the same. Some have high energy but weak magnetic fields, which cause little damage to infrastructure. Others have strong magnetic fields but weak energy. These are the ones we should worry about, but it is hard to spot them in the historical record because it is the energetic particles alone that cause the carbon-14 spikes that researchers look for.

This was demonstrated by the 1859 Carrington event, when the battering of the Earth's magnetic field induced electricity to flow in the world's telegraph lines, stunning operators unconscious and causing telegraph offices to burst into flames. Yet there is no sign of it in the carbon-14 records.

Conversely, a CME with a huge number of high-energy particles struck in 1956, yet it caused little disruption to communications. And when the Hydro-Québec power grid was knocked out in 1989 by a CME, it wasn't the one with the highest energy that year. That occurred six months later. "The whole thing ends up being very confusing," admits Melott. "We are faced with trying to deduce new science from complicated data."

The more measurements we can study, the better. Usoskin, for example, has turned from tree rings to the lunar rocks brought back by the Apollo missions. Exposed on the moon's surface, the rocks act like sponges soaking up all the energetic particles that the sun has been spitting out during the course of the moon's 4.6-billion-year lifetime.

They should allow us to know the size of the greatest solar events that have ever exploded from the sun, and not just the ones during the last two millennia. Perhaps the next time we see serpents in the sky, we will truly appreciate how dangerous living next to a star can be. ■

TOM GAULD

Liquid asset

With its icy poles and morning dew, the moon is a lot wetter than we ever imagined says **Dana Mackenzie**

IT IS the best of times and the worst of times for lunar scientists. "We've got a revolution going on in our understanding of the lunar surface," says Rick Elphic of NASA Ames Research Center in Mountain View, California. Three recent missions have found an unexpectedly large supply of water on the moon that could both quench the thirst of future lunar dwellers and produce fuel for missions to other places in the solar system.

Yet the prospect of astronauts getting there any time soon has all but dried up. In February 2010, President Barack Obama announced his intention to cancel NASA's Constellation programme, which included plans to get astronauts back to the moon by the early 2020s. His decision left the US without a reliable means of transport to low Earth orbit, let alone the moon.

Even so, the 2010s are shaping up to be a boom time for lunar science. But not from the direction you might expect. In 2013 China became the third country to successfully make a soft landing on the moon, and future Chang'e moon missions are currently under preparation. Meanwhile, India is hoping to build on the success of its Chandrayaan orbiter with its first lunar rover, and Russia and Japan are not too far behind.

What has reinvigorated lunar science most of all are the discoveries of water made in 2009 by NASA's Lunar Reconnaissance Orbiter (LRO) and Lunar Crater Observation and Sensing Satellite (LCROSS), as well as India's Chandrayaan-1.

"Not only is there water on the moon," says Carle Pieters, the chief scientist for the Moon Mineralogy Mapper on Chandrayaan-1, "but there are three different kinds of water."

Pieters is referring to the discovery in 2008 of trace amounts of water in volcanic glasses from deep in the moon's interior, surface water detected by Chandrayaan-1, and buried water at the poles dug up by LCROSS. "They are all different, and they all have different sources and implications," she says.

"This is not your father's moon," says Greg Delory, a space scientist at the University of California, Berkeley. "Rather than a dead and unchanging world, it could be a very dynamic and interesting one."

> **"The moon is far from a dead and unchanging world"**

Support for a wet moon has ebbed and flowed throughout history. After Galileo's telescope proved in the early 1600s that the moon was another world, it was widely assumed it had water. The moon's dark blotches were named "maria", Latin for "seas". Yet by the end of the 17th century the evidence was already beginning to point towards a dry moon. More powerful telescopes discerned craters within the maria, which would not be visible if they were indeed oceans.

Fast forward to 1969, and the consensus had swung firmly in favour of an arid moon. The two Apollo 11 astronauts who landed on one of those so-called seas found it to be a dry lava plain. Back on Earth, the Apollo rock and soil samples were pronounced "dry as a bone". In fact, they were a great deal drier, because living bone is never less than 10 per cent water by weight.

But even then, there were cracks in the orthodoxy. Lunar soil contains hydrogen ions carried from the sun by the solar wind. Constantly bombarding the moon, these ions can knock atoms loose from rocks, creating a plethora of oxygen atoms with dangling bonds. This could mean that hydrogen ions might attach to the oxygen to form hydrated minerals, hydroxyl ions (OH^-) or water (H_2O), one ion or molecule at a time.

Everett Gibson of NASA's Johnson Space Center in Houston, Texas, found evidence that this was more than a theory. In 1977, he showed that the Apollo rocks released water and hydroxyl when heated. Nevertheless, he failed to change the conventional wisdom that moon rocks were dry. There was a possibility that the samples had been contaminated by the supposedly dry nitrogen they were stored in on Earth. "The 'dry' nitrogen had about 20 parts per million of water," says Larry Taylor, who studies lunar rocks at the University of Tennessee in Knoxville. Alternatively, heating could have caused the hydrogen implanted by the solar wind to react with iron oxides in the rock, so that the water was actually formed in Gibson's lab, not on the moon.

Around the same time, the late James Arnold of the University of California, San Diego, suggested looking for water near the lunar poles, which were not visited by Apollo. Because the moon's poles receive only grazing sunlight throughout the year, Arnold pointed out that the base of a deep crater near a lunar pole would never see any light. Such craters could act as "cold traps" for water or any

other volatile compounds in the tenuous lunar atmosphere.

Taylor compares the cold traps to a glass of ice tea on a summer day: "You can sit there and watch it gather all the moisture out of the air, and start dripping water. That's what the poles are doing."

It took 15 years before the "ice tea" theory was tested. In 1994, radio telescopes on Earth picked up radar waves bounced off the moon's surface by a satellite called Clementine. The results were tantalisingly inconclusive. Clementine got only one good look at the south pole and while the radar did pick up what looked like the signature of water ice, the same type of signal could have been produced by the roughness of the lunar surface.

In 1998, Lunar Prospector orbited the moon carrying a neutron spectrometer, an instrument widely used in oil-prospecting to look for water and hydrocarbons. It measures the amount of hydrogen present, which is a plausible proxy for the amount of water. Lunar Prospector definitely saw hydrogen – enough that the soil could contain 1.5 per cent water by weight. Of course, that depends on whether you believe the assumption that water accounts for the hydrogen. The hydrogen atoms could instead be unattached, or be present thanks to other hydrogen-bearing compounds such as methane or ammonia. Also, Lunar Prospector could not resolve features smaller than 50 kilometres, so it could not tell whether the putative water was indeed concentrated in the permanently shadowed craters or spread out uniformly.

Lunar dew

The real test would be to land on the lunar surface and dig up a sample of the soil. Lunar Prospector did the next best thing: it crash-landed near the lunar south pole in 1999. Mission controllers had hoped to blast enough water from the moon to be able to detect it from Earth – but none was seen. A similar attempt with a European Space Agency probe called SMART-1 in 2006 also failed to detect any signs of ice. Either the water didn't exist, or the two spacecraft were too small, hit the moon too glancing a blow, or simply hit the wrong places.

The stage was now set for two discoveries that would radically change our picture of the moon. In October 2008, India launched Chandrayaan-1, equipped with an imaging spectrometer, an instrument which had never gone to the moon before. It allows us to determine exactly which chemicals occur at which pixels in an image.

Soon after Chandrayaan-1 began mapping the moon, Pieters and her team realised that they were seeing large areas of hydroxyl and water. At first they couldn't believe their results, but team member Roger Clark remembered seeing something similar when he worked on the Cassini-Huygens mission to Saturn and its moons.

Cassini also carries an imaging spectrometer. Like an athlete going through practice workouts before the real competition, Cassini trained its spectrometer on the moon during a fly-by in 1999.

During a team discussion in 2009, Clark mentioned Cassini picking up hydroxyl and water on the moon. Then Jessica Sunshine, a Chandrayaan-1 team member who was also

Gas station in the sky

Lunar water and other volatiles will be essential ingredients for any sustained human presence in space – if that presence ever materialises.

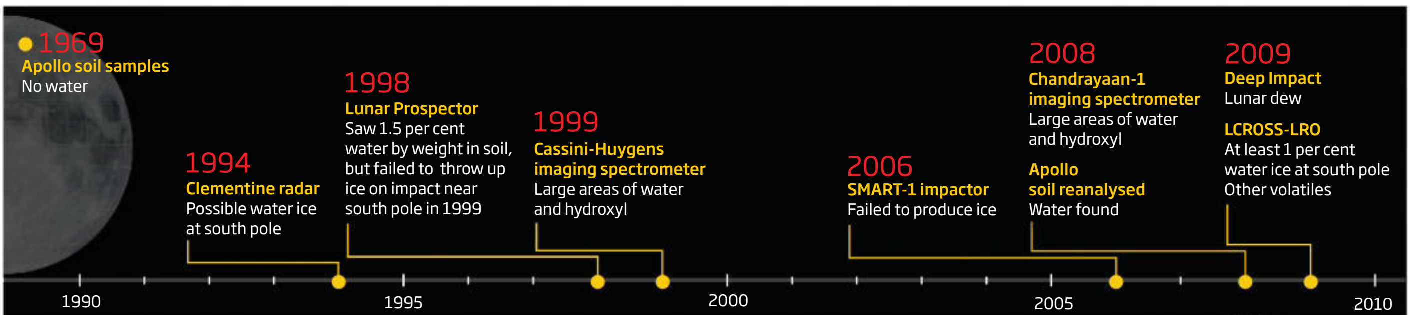
Paul Spudis of the Lunar and Planetary Institute in Houston, Texas, divides space exploration into three stages: "Arrive, survive and thrive." We have already arrived at the moon, thanks to Apollo. To survive, we don't necessarily need lunar water. "You can take your water with you and recycle," says Taylor. But the availability of water makes survival much easier, because it frees future astronauts from umbilical dependence on Earth. With locally produced water, they can drink, create a breathable atmosphere, make concrete, build a shelter against cosmic rays and grow plants.

For us to thrive on the moon's surface, water and volatiles are even more crucial. As Taylor says: "The moon is a gas station in the sky." The true economic value of water – not to mention the frozen methane that was also detected by LCROSS – is as a propellant for interplanetary travel. The water can be converted for use as fuel by separating it into oxygen and hydrogen, while the methane is useful as it is. Both of these substances would be more expensive than gold if they had to be carried on spacecraft from Earth; far cheaper to mine them on the moon, if at all possible.

Spudis has previously estimated that there might be 600 million tonnes of water in the moon's north polar region, which would be enough to launch one space shuttle a day for 2000 years. While that's a cute factoid, not all the water will be easy to extract. Spudis's radar instrument on Chandrayaan found evidence of water in 40 different small craters near the north pole, with the best examples on the floors of the Peary and Rozhdestvensky craters. All of them do have permanently shadowed regions, but the presumed water deposits extend outside of the shadow. Other nearby craters that look similar do not have water deposits for reasons that are still unclear.

Timeline of lunar water

Many missions have searched for water on the moon, with mixed results



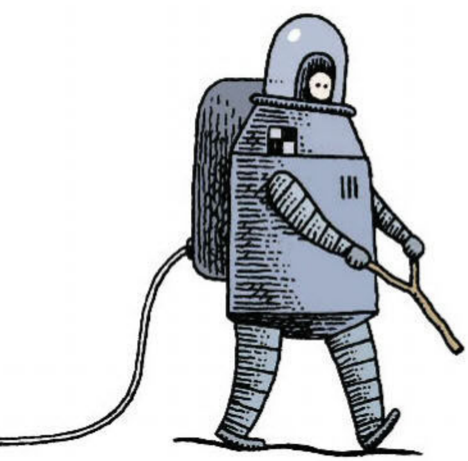
working on the Deep Impact mission to visit comets, spoke up. “Deep Impact is going by the moon in June, so I’ll be able to tell you what it sees.” It also carries an imaging spectrometer.

Sure enough, Deep Impact confirmed the Cassini and Chandrayaan-1 measurements. “Both of those instruments really helped us understand what was occurring there,” says Pieters. In fact, Deep Impact added a new piece of information: the water and hydroxyl seem to disappear during the lunar day, only to reappear at sundown and sunrise, like dew. This “dew” is, however, only a few molecules deep, so the lunar soil is still drier than the driest desert on Earth.

The discovery of mobile surface water was so unexpected that scientists are still debating where it comes from. One possibility is that individual molecules are created by the solar wind and hop around the lunar surface for a while, until they either get caught in a cold trap or escape out to space.

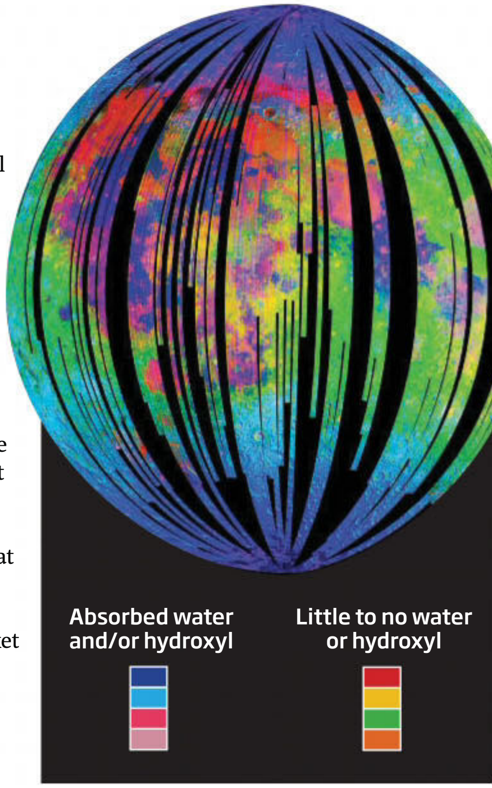
Lunar scientists received another jolt when LCROSS crashed into a crater called Cabeus that October. LCROSS was designed to do what Lunar Prospector and SMART-1 could not. It walloped the moon head-on with a spent rocket engine the size of a large van, followed by a “shepherding satellite” that observed the impact from directly overhead before it, too, crashed into the moon 4 minutes later. It had the best possible vantage point for seeing whether the debris contained water.

In choosing to switch the impact site to Cabeus, LCROSS’s lead scientist Tony Colaprete had gone for a very deep crater with a very high ridge on its edge, which effectively blocked astronomers’ view of the impact from Earth. It was a calculated gamble. From earlier satellite observations, Cabeus appeared to have the highest concentrations of water, and Colaprete was betting that the shepherding



Water, water everywhere

This 2009 lunar map made by the Chandrayaan spacecraft shows water and hydroxyl are spread more extensively than anyone thought



SOURCE: R CLARK / 41ST LUNAR AND PLANETARY SCIENCES CONFERENCE

satellite would be able to see it without any help from Earth-based telescopes.

“When Tony told us he was changing the [impact] site, we honestly thought we were screwed,” says Pete Schultz, a member of the LCROSS team. Indeed, from Earth the impact did at first seem to be a dud, but within days the team knew they had hit a water-rich site. The spectra showed clear signs of water, and the team voted to go public with their findings in November, a month ahead of schedule.

It is now certain that at least 1 per cent of the excavated material was water ice, perhaps as much as several per cent. To put it in simpler terms, the LCROSS impact site was damper than the driest desert on Earth.

But the biggest surprise was an abundance of other stuff in the debris plume, especially volatile compounds like carbon dioxide, ammonia, sulphur dioxide, methane and ethylene. “Maybe we can distil alcohol and make a little moonshine!” jokes Jack Burns at the University of Colorado, Boulder.

While water can be created on the moon by the solar wind, these other compounds cannot. If they are present in Cabeus, it is likely that they came from an outside source – a meteoroid or cometary impact. That could mean that localised deposits are far richer in water than the solar wind theory predicts.

Between 2009 and 2011, LCROSS’s sister spacecraft, LRO, continued to gather information. One of its instruments, Diviner, has measured the lunar temperature from orbit. Instead of guessing where cold traps are likely to be on the basis of solar illumination maps, we can now measure where they are. In many cases, they extend beyond the range of permanent shadow.

Diviner also found that the shadowed regions themselves are colder than anyone expected. In fact, some of them are even colder than Pluto, where temperatures of 30 to 40 kelvin are typical.

LRO’s neutron spectrometer, called LEND, is also refining Lunar Prospector’s maps of hydrogen deposits. LEND’s results are sharply at variance with the ice tea theory, identifying regions that are potentially as hydrogen-rich as Cabeus but are not located anywhere near a permanently shadowed crater. It will take time for researchers to assimilate these results, determine how reliable they are, and develop new hypotheses to account for them.

The discovery of water raises all sorts of scientific questions, which inevitably morph into questions about resource extraction. Clive Neal, chair of NASA’s Lunar Exploration Analysis Group, checks off a few of them: “Where does the water come from? How long has it been there? How much is there? What form is it in? Is it a sheet, or is it patchy? What are the complications of extracting it from an environment that is around 30 or 35 kelvin? How much is it going to cost?”

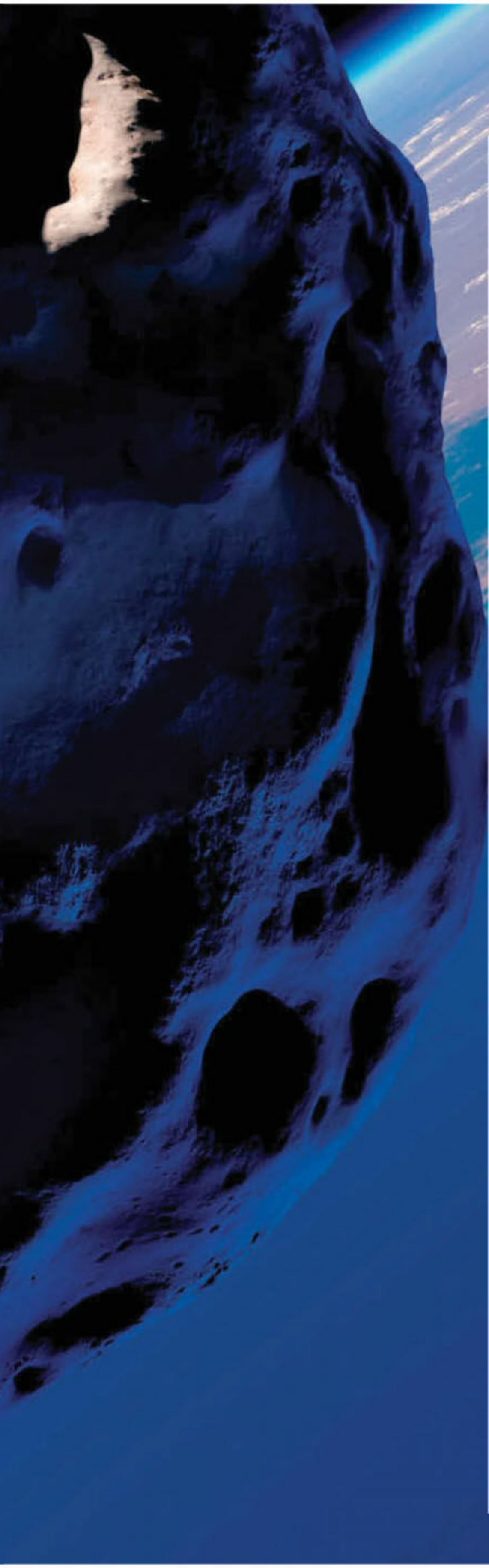
The best way to answer these questions, most lunar scientists agree, is to send robotic landers to the moon. Ideally, they would be rovers, like the ones that have proven so useful on Mars. A rover could carry a neutron spectrometer, for instance, as a high-tech dowser for subsurface water. Because the moon is only 1.3 light seconds away, scientists on Earth could operate a robot in near-real time – a distinct advantage when compared with the way the Mars rovers are controlled.

Given the scarcity of money and the uncertainties of politics, it is still unclear how to get from here to a sustainable human presence on the moon. For the next 10 or 20 years, the only Earth creatures on the moon will have silicon brains. However, the year 2009 may well go down in history as the year we struck water on the moon. ■

New moon

Earth may have many more moons than you think. Perhaps we should pay one a visit, says **Stuart Clark**

DETLEV VAN RAVENSWAAY/SCIENCE PHOTO LIBRARY



JUST over a century ago, something strange split the sky across North America. On 9 February 1913, eyewitnesses reported dozens of burning fireballs cutting a swath across the night sky. It was a display unlike any other meteor shower. Instead of shooting stars raining down in all directions, a train of bright fireballs moved slowly and deliberately over much of the continent.

The first sighting was in Saskatchewan, Canada. Burning red-hot from its passage through the atmosphere and trailing streaks of vapour, the meteor train moved south-east, passing just a few kilometres north of New York and then out over the Atlantic Ocean. Final sightings of the spectacle came from Bermuda and a steamer ship near the equator.

The distance between the first and last observing points was 9200 kilometres. To be seen over such an expanse, the meteors must have been in orbit around our planet. The conclusion was compelling: what people had seen that night was probably the break up of a small, previously undiscovered moon of Earth.

We are now realising that the events of 1913 may not be unique. Computer models of asteroid orbits are showing that small space rocks a few metres across can become lodged in Earth's gravitational field if they stray too close. Only a tiny fraction of them break up and hit our planet. Most orbit unseen for months or years, somewhere beyond the moon, before slipping safely and silently back into deep space. But while they remain close, they are mini-moons of Earth. Not only are they turning out to be more common than anyone thought, they could play a vital role in unravelling our solar system's secrets.

It is not unheard of for a planet to capture a small celestial object. Jupiter is a master of the art: it is 320 times more massive than Earth, and also orbits five times farther away from the sun. At that distance, the sun's gravity is much weaker, so Jupiter can wrestle objects away from it and clutch its prey more tightly. Jupiter's most notable recent catch was comet Shoemaker-Levy 9. The giant planet's gravity subsequently pulled the comet to pieces and swallowed it in a series of spectacular explosions in July 1994.

Thankfully for us, Earth's gravity is much weaker, meaning such violent acts are extremely rare. Most of the objects that do make it to Earth originate in the asteroid belt between the orbits of Mars and Jupiter. However, telescopes designed to identify asteroids that may one day smack into Earth have found growing numbers of objects in orbits across the solar system. Most are small, fragments of once larger objects that have broken up in collisions over the aeons. Any such small body that finds itself passing by on an orbit similar to Earth's is likely to be snagged and yanked onto a course that takes it around our planet instead – if only for a short while.

Moon trackers

Mikael Granvik at the University of Helsinki in Finland and his colleagues are among those dedicated to tracking down these celestial fly-by-nights. Calculations by Granvik's group show that mini-moons are likely to be a few metres across and orbit slowly at up to 12 times the distance of the moon. The course they chart around Earth is a delicate one because of perturbations in the gravitational field from the sun and other planets (see "Mini-moon or quasi-moon?", page 30). As a result, Granvik's model predicts that most captured objects drift off again, spending on average just 9 months in orbit. Perhaps the biggest surprise, however, is that such temporary mini-moons are common. "There is probably one up there right now," says Granvik.

Finding a mini-moon is no easy matter because their small size means they reflect little light. Present surveys, such as the one conducted with the Pan-STARRS telescope in Haleakalā, Hawaii, are looking for potentially hazardous near-Earth asteroids. But they are not really powerful enough to search for metre-sized mini-moons.

What Granvik and others do see often turns out to be space junk masquerading as small asteroids. Out of the first six objects investigated, says Paul Chodas at NASA's Jet Propulsion Laboratory in Pasadena, California, "five have turned out to be upper stages of rockets," (see "Space junkie", page 30). ›

MINI-MOON OR QUASI-MOON?

Discovered in 1986, asteroid Cruithne shot to fame when astronomers spotted that it takes a year to orbit the sun and never strays too far from Earth. This led to it being dubbed Earth's second moon. But according to Mikael Granvik at the University of Helsinki in Finland, that is stretching things a little too far. Cruithne is an example of a quasi-moon – its path is dictated by the sun's gravity rather than our planet's. "If you took away the Earth, a quasi-moon's orbit would not be affected," says Granvik.

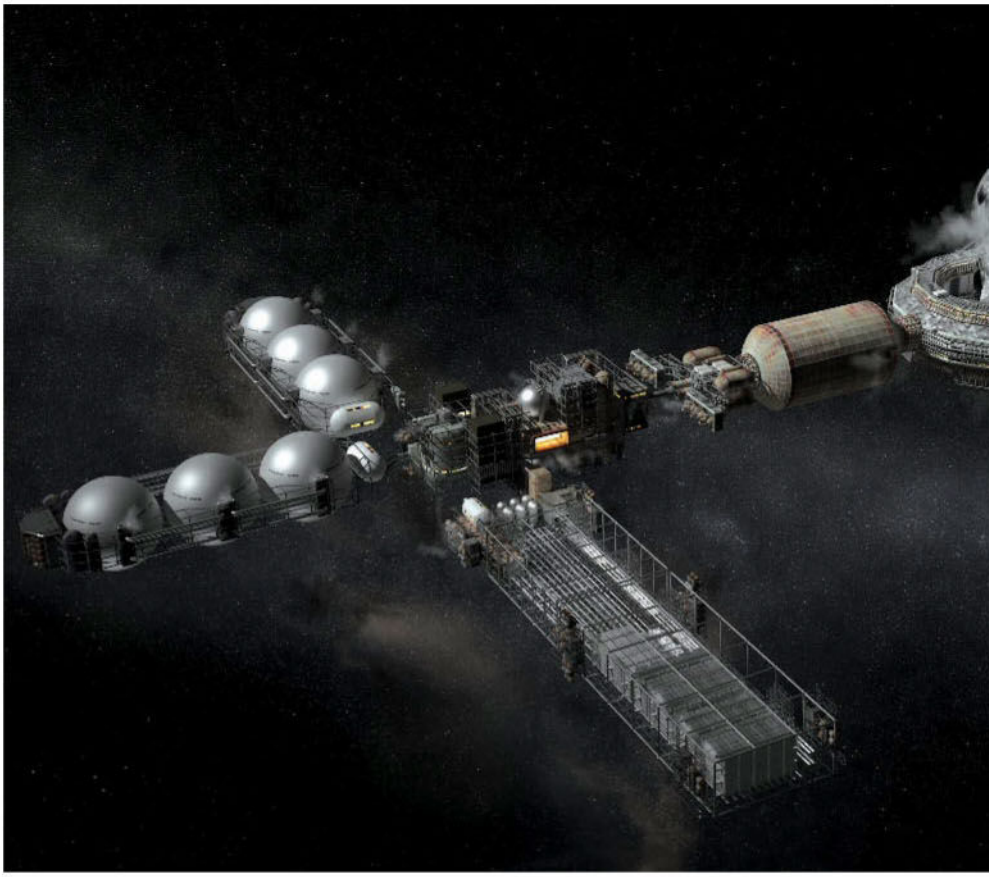
In contrast, mini-moons are actually in Earth's gravitational clutches – at least for a while. A mini-moon's orbit is determined by a delicate balance between the gravitational fields of Earth, the sun and other celestial bodies. This is what makes them susceptible to falling into orbit around Earth in the first place, and then prone to drift off again.

SPACE JUNKIE

Paul Chodas studies near-Earth objects, and part of his job is to investigate the reports of possible mini-moons.

Based at NASA's Jet Propulsion Laboratory in Pasadena, California, Chodas's most notorious case is asteroid 2010 KQ, discovered in May 2010 by the Catalina Sky Survey in Tucson, Arizona. Just a few metres across, it seemed a dead ringer for a mini-moon. Then infrared observations showed that its composition resembled no known asteroid type, but was reminiscent of metal rocket parts. Chodas provided the clinching evidence by showing that 2010 KQ had been very close to Earth in 1975, although its orbit is not known well enough to associate it with a specific rocket launch.

He was also responsible for the calculations showing that another mini-moon, discovered in September 2002, was probably Apollo 12's upper stage returning to Earth for a lap of honour. It had been left in a loose Earth orbit back in November 1969, had slipped into orbit around the sun, and been temporarily recaptured by Earth during 2002 and 2003.



BRYAN VERSTEEG/SPACEHABS.COM

That leaves one. On 14 September 2006, the Catalina Sky Survey detected an object in Earth orbit. Designated 2006 RH_{120}, it was calculated to have been captured by Earth in July of that year. As astronomers watched, it made three leisurely orbits over the following 12 months, one of them bringing it inside the orbit of the moon, and then drifted away again.

This time everything fitted. To distinguish it from space junk, Chodas analysed the body's orbit. Asteroids move primarily under the pull of gravity because they are dense, whereas space junk tends to be hollow and susceptible to being pushed around by the pressure of incident sunlight. The weight of evidence pointed to 2006 RH_{120} being an asteroid some 5 metres across. It is now moving away around the sun in a similar orbit to Earth. By 2017, it should be on the opposite side of the sun from us. Its return visit is likely to take place around 2028.

Granvik suspects that astronomers have sighted other bona-fide mini-moons but have simply disregarded them. "When observers see an object in Earth orbit," he says, "they tend to think it is just space junk and so throw the data away." He is hopeful that new surveys will lead to the discovery of many more mini-moons. The Large Synoptic Survey Telescope, planned for completion on the slopes of Cerro Pachón in Chile in 2019, is an 8.4-metre telescope that will survey the entire sky once a week looking for asteroids. It should be able to spot mini-moons easily and quickly. "If we do start to routinely find mini-moons in the future, we will have the opportunity to study a population of small asteroids that we have not seen before," says Granvik. "We could easily send spacecraft to them."

The scientific pay-off of such missions would be large indeed. Asteroids are the leftovers of planet formation. They are the fragments of rock and metal that never managed to coalesce into larger worlds. As such, they hold clues about the way the planets formed, such as the raw ingredients that went into those worlds – including the organic components that Earth managed to cook up into life.

Fly me to the moon

Considering the great pains that planetary scientists have gone to in recent years to bring back a few specks of dust from an asteroid, a mission to a mini-moon would offer convenience and bounty beyond their wildest dreams. The Japanese space agency's Hayabusa probe had already suffered its fair share of setbacks and delays when it finally blasted off towards asteroid Itokawa in 2003. It was hit by a violent solar storm that damaged its solar panels, reducing its on-board power and slowing the spacecraft down. On arrival at Itokawa in 2005, moves to stabilise the

Mini-moons orbiting Earth could bring asteroid mining closer to reality

spacecraft failed and communications were lost during the attempted landing. On top of that, the sampling device did not work correctly. Nevertheless, the spacecraft limped home and delivered its precious cargo of asteroid dust in June 2010.

Instead of a spacecraft taking months or years to journey into space to rendezvous with asteroids, it could be at a mini-moon after only a few weeks, or even days, of travelling time.

"At just a few metres across, they are small enough that we could even bring a complete one back to Earth for analysis," says Granvik.

Beyond the value of the science, there could be other – more lucrative – rewards for bringing a mini-moon down to Earth: precious metals.

Asteroids come in three basic types. M-types are largely metal and were once at the hearts of now-shattered protoplanets. S-types are stony asteroids but are noticeably rich in metals such as iron, nickel and magnesium. C-types are the most common and are composed of elements in their average cosmic abundances but without the hydrogen and helium gases. Even though C-types are not notably enriched, they still contain enough precious metals to make them extremely valuable if they were brought to Earth.

The last time people were talking about mining asteroids for mineral resources, the chances are they were wearing a tank top and corduroy flares. It was all part of the Apollo-era optimism about living and working in space – and it collapsed along with NASA's budget sometime in the 1970s. Now the idea, unlike the tank top, is back in fashion.

The reason for the renewed interest is the upward trend in the price of gold and other base metals during the past decade. Back in 1994, William Hartmann at the Planetary Science Institute in Tucson, Arizona, estimated that a 2-kilometre-wide asteroid would be worth $25 trillion in metal and mineral resources (see diagram). That's enough to pay off the US's $19 trillion national debt, use the loose change to settle up for Greece and still make the investors very rich indeed. "I don't see how you can look at any economic study of Earth and not think about the potential resources of the inner solar system," says Hartmann.

The trouble is, of course, that such resources are not exactly easy to reach. Mini-moons could change that. Although they are just a thousandth of the diameter of the asteroid that Hartmann used in his 1994 example, they are far easier to reach. "Once Earth has captured these asteroids, they become accessible to us," says Chodas, although he remains unsure about the practicality of mining in space.

Aerospace engineer Hexi Baoyin and his colleagues at Tsinghua University in Beijing, China, are taking the idea further. Having independently identified how small asteroids can be naturally captured by Earth, they have suggested that some closely approaching asteroids could be nudged into Earth orbit, either by slamming projectiles into them or using more subtle methods like erecting solar sails on them. This, they propose, could be one of the best ways to make mining near-Earth asteroids possible.

"Instead of taking years to journey to an asteroid, a spacecraft could be at a mini-moon within weeks"

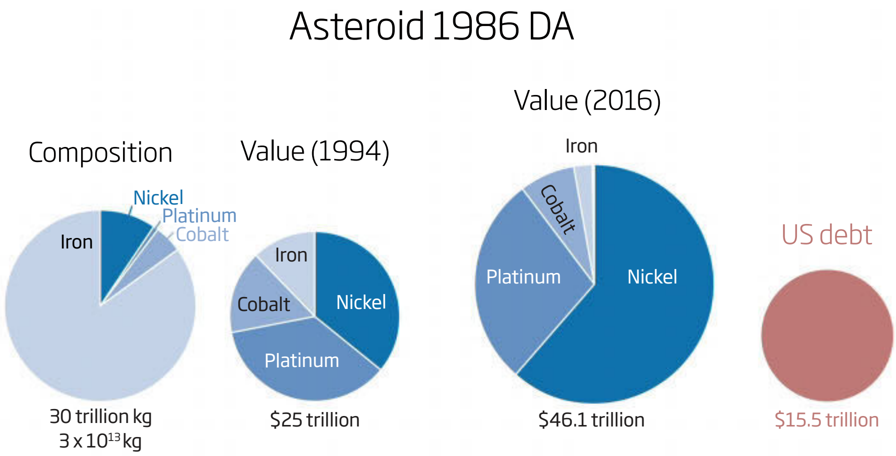
As the world's human population increases, so the demand for resources will grow. Some of Earth's resources are already expensive to mine and this may make asteroids increasingly tempting targets – especially if the cost of space missions drops dramatically thanks to the efforts of private space companies such as SpaceX in Hawthorne, California. It is one of several companies in which the US government is investing to try to bring the cost of launching each pound (0.45 kilograms) down to below $500.

Even so, Chodas is sceptical. "Getting the equipment to these asteroids is expensive, getting the minerals back is even more so," he says. "I'm not sure space travel will ever be cheap enough to make mining asteroids viable."

Even if asteroid mining never takes off, mini-moons are still a source of wonder. Why spend billions travelling to an asteroid when they are gently knocking on our front door? Unseen they may be, yet as we gaze out into the night sky, there is every reason to think that they are up there, taking turns to orbit our planet, like celestial fruit just waiting to be picked.

Cosmic cornucopia

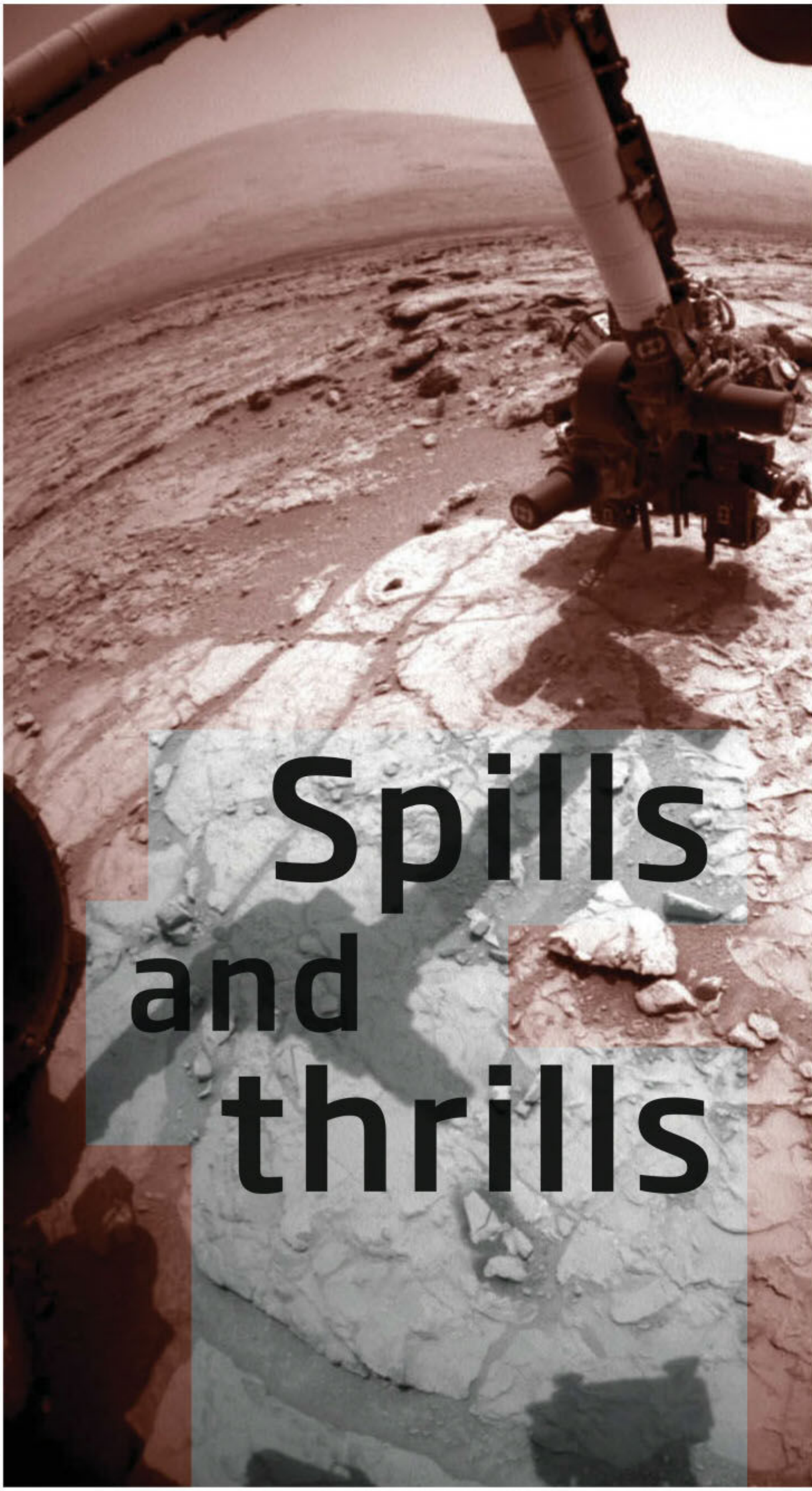
Asteroids could be a valuable source of metals. In 1994, William Hartmann at the Planetary Science Institute estimated the value of a 2-kilometre-wide metal rich asteroid



SOURCE: LONDON METAL EXCHANGE/PLATINUM TODAY

Spills and thrills

An accident on board Curiosity didn't sound good, but it helped the Mars rover hit pay dirt after all, says **David L. Chandler**

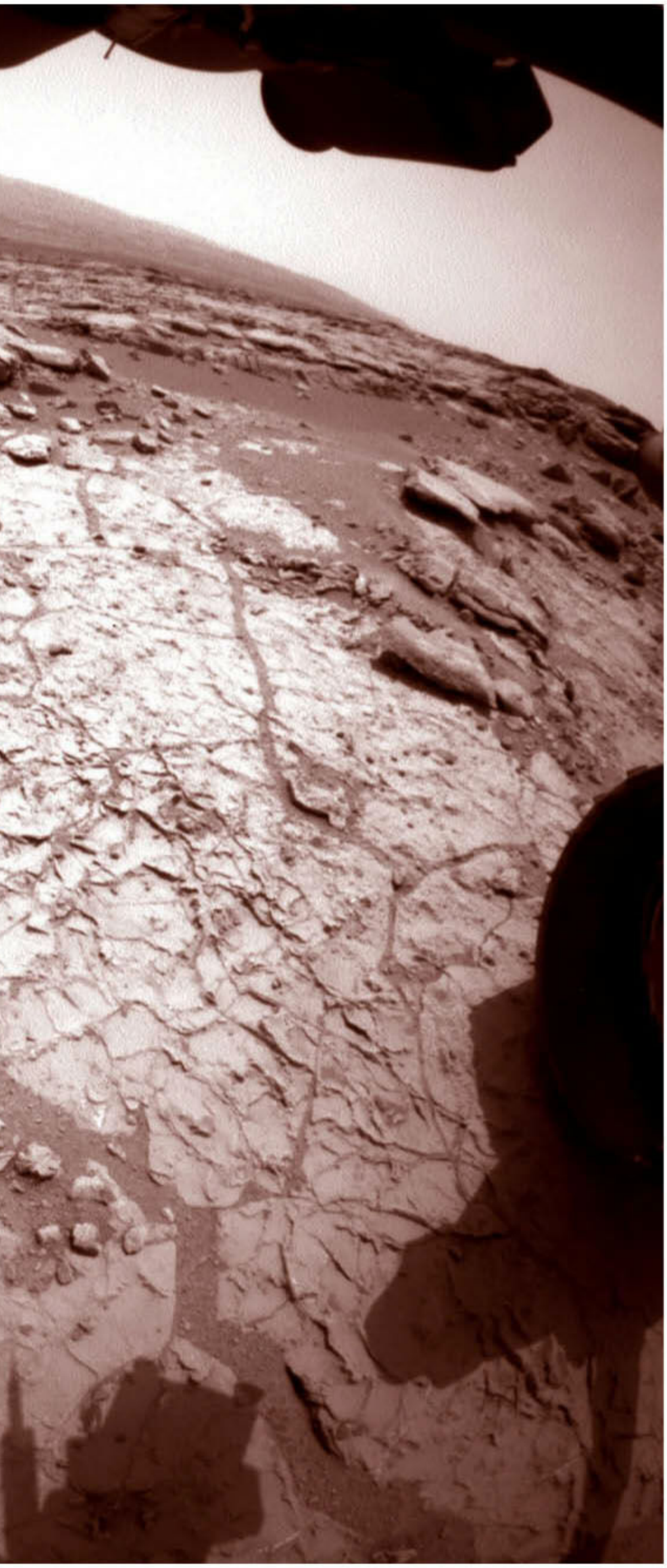

NASA/JPL-CALTECH

REPORTERS and camera crew made sure they got to the conference centre in San Francisco early on 3 December 2012. They were expecting historic news from Mars. Speculation was rife: what exactly had NASA's newest and biggest rover found? Curiosity's project scientist John Grotzinger had let slip his excitement in a radio interview two weeks earlier. He was explaining how the rover had analysed its first scoops of Martian soil from a pile of windswept sand, then added: "This data is going to be one for the history books. It's looking really good."

That could only mean one thing, right? Signs of life! Now Grotzinger and others faced a packed pressroom at the annual meeting of the American Geophysical Union to announce… almost nothing. Yes, Curiosity had technically detected organic molecules, a prerequisite for life on the Red Planet. But no, the science team emphasised, this was not significant – the organics were probably from Earth and this was just a successful first test that showed Curiosity's instruments were working properly. To those who had devoted nearly a decade of work to this project, this was exciting news. But it was hardly the earth-shaking headline that the reporters had been expecting.

Fast-forward several weeks, however, and Curiosity's first soil sample turned out to be a big deal after all. It changed our ideas about the Martian surface. And it added yet another twist in the decades-long quest to find signs of past, or even present, biological activity on Mars.

Curiosity is more than just a camera on wheels. It carries by far the most sophisticated suite of scientific instruments ever sent to another world. As well as a wide variety of imaging instruments that can take pictures at many different wavelengths and at ranges from the microscopic to telescopic, it can sample air and has a scoop and a drill for obtaining samples of soil and rock. These can then be analysed in cutting-edge on-board chemical laboratories to determine the mineralogy, chemistry, molecular compounds and even the isotopic ratios of elemental constituents.



Curiosity is looking for signs that Mars is or was once habitable

Of all these instruments, perhaps the most advanced is a cluster of devices called SAM, short for Soil Analysis at Mars. It takes rock samples and vaporises, burns or mixes them with liquid compounds in order to detect some organic molecules that otherwise could not be identified.

Organic molecules are indeed what SAM found when it baked its first few samples of soil close to Curiosity's landing site. The team soon realised, however, that these molecules were not from Mars. They almost certainly came from the reaction of a chemical containing carbon and hydrogen called MTBSTFA that was brought along from Earth. SAM carries nine phials of the stuff to mix with Martian soil in order to identify much more complex organic materials, such as amino acids.

One of the phials had sprung a leak. "This wasn't a case of some subtle bit of cleaning fluid or some residual chemical," says Chris McKay, a planetary scientist at NASA's Ames Research Center in Moffett Field, California, and a member of the SAM team. "This was like a big spill in the pantry."

Viking controversy

That might sound like bad news, but the results brought an unexpected benefit. They revealed clear-cut evidence for perchlorates, a highly reactive chlorine compound, in the Martian soil.

To understand why perchlorates are so important, we need to turn the clock back to one of the most controversial chapters in Martian exploration history. In 1976, NASA's twin landers, Vikings 1 and 2, touched down at two locations on Mars and began a series of experiments. Each lander carried three different life-detection tests and a device called a gas chromatograph mass spectrometer for detecting different kinds of molecules in the soil. When the spectrometers analysed heated soil samples, they sometimes detected bursts of oxygen and carbon dioxide. This suggested the presence of organic molecules in the Martian soil, which were being broken down on heating.

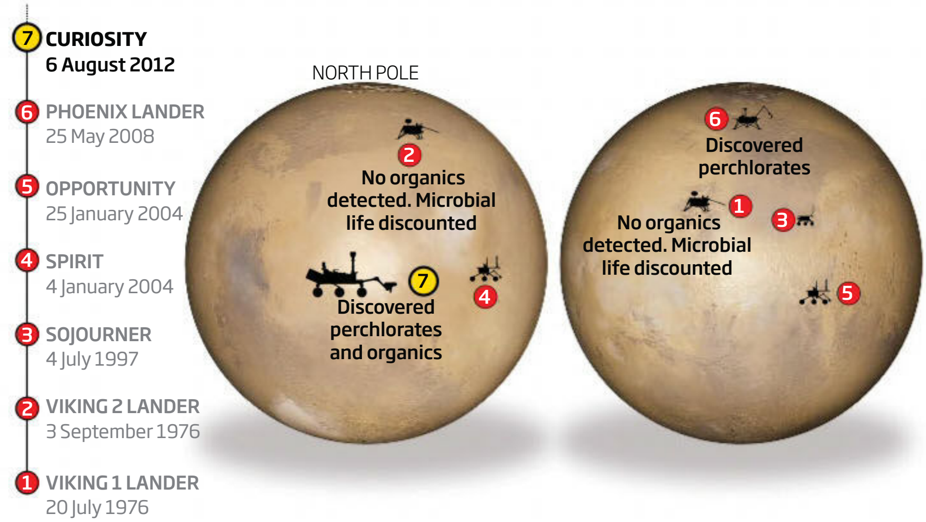
At the time, though, the results were interpreted as the result of terrestrial contamination – perhaps from solvents used to clean the equipment. Not everyone accepted that view: the oxygen and CO_2 appeared only when Mars soil was present in the test chamber and not during control runs with the chamber empty. But the contaminant explanation stuck.

Two researchers who have challenged that view are McKay and his colleague ›

NASA/JPL-CALTECH/MALIN SPACE SCIENCE SYSTEMS

From Viking invasions to big Curiosity

Curiosity is the largest explorer ever to land on the Red Planet. Its goal is to find out if Mars is or was habitable



Rafael Navarro-Gonzalez at the National Autonomous University of Mexico. In a paper published in 2010, they argued that the CO_2 seen in the Viking tests really was a sign of organic materials indigenous to Mars, and could be down to highly reactive soil chemistry – specifically perchlorates acting on organic compounds in the soil.

Their view was based on experiments they carried out on soil samples collected over the past decade from the arid, lifeless Atacama desert in Chile, probably the closest we can get to Martian-like soil here on Earth. When McKay and Navarro-Gonzalez added magnesium perchlorate to soil samples and heated them, they found that nearly all of the organic compounds present in the soil reacted to form water, CO_2 and chloride compounds. So the presence of perchlorates on Mars could explain the Viking results.

What's more, they could up the stakes. The apparent absence of organics has always been the primary argument against one of Viking's contentious life-detection experiments, known as the labelled release test. It involved taking a pinch of Martian soil and adding a nutrient solution containing the kinds of chemicals that terrestrial organisms would consume. The carbon in these nutrients was radioactive carbon-14, so if any microbial life devoured the nutrients the CO_2 they exhaled would be radioactive too. Sure enough, the labelled release experiments on both Vikings detected radioactive CO_2. And the reaction appeared to stop when the soil was heated to temperatures that would kill any microbes.

Although these results met all the criteria that the Viking science team had agreed as positive signs of living organisms before the mission, the apparent lack of organic material in the soil was baffling. If life was present in the soil, then there should be an abundance of organic compounds left over from the decay of billions of dead microbes. But the lack of organics – or at least the dismissal of the organic results – was taken to mean that life could not have been present, despite the apparently positive results from the labelled release test.

McKay and Navarro-Gonzalez's conclusions about Viking have been harshly criticised, even ridiculed, by some other researchers. However, further backing for their idea comes from NASA's Phoenix lander, which found perchlorates in the soil at its landing site near the Martian north pole. Even so, most scientists thought that perchlorates were unlikely to be widespread, and so there would be little chance of them turning up where Curiosity and Vikings 1 and 2 landed.

"Curiosity's mission is still ongoing. Its potential for returning stunning new findings from the Red Planet remains untapped"

Now Curiosity has proved them wrong thanks to the spill of organic chemicals in the SAM instrument. Without it, McKay says that the amount of perchlorate in the soil would be too small to detect. The sheer size of the leak meant that the perchlorates reacted strongly with the organic compounds. "We saw chlorine compounds up the wazoo," says McKay. "The presence of the organics was a huge benefit."

Why this perchlorate compound should be so widespread on Mars remains a mystery. "It was unexpected, and it's unexplained," says McKay. "On Earth, it exists, but it's rare, even in the Atacama desert."

McKay and Navarro-Gonzalez went on to speculate that organic compounds are widespread on Mars, too. That's not the same as saying there are signs of life on the Red Planet. Each year more than 1000 tonnes of organic material lands on Mars in the form of meteorites carrying compounds rich in carbon and hydrogen. What was still unclear was whether it remained intact or was destroyed by ultraviolet radiation, cosmic rays and chemical reactions in the soil.

Early days

Answering this question first involved figuring out ways of cleaning up the mess. Fortunately, the team were able to work around the problem by simply compensating for it in their data. "It's not a fatal problem," said McKay, shortly after the leak occurred. "We just have to correct for it."

There was good reason for such optimism. By this point, Curiosity's mission had barely

begun, and its potential for returning stunning new findings from the Red Planet remained mostly untapped. Steve Squyres leads the science team studying the findings from the previous generation of Martian rovers, Spirit and Opportunity. "The first really significant discovery we made from Spirit came 800 days into what had been planned as our 90-day mission," he points out. Curiosity's mission was originally planned for at least two years, and is now well into its fourth. "It's probably going to outlive many of us on the team," Squyres says.

As the rover worked its way across Gale crater toward the towering slopes of its primary destination, Aeolis Mons, known as Mount Sharp, it traversed areas where deposits of clay minerals had already been clearly detected from orbit. As clays usually form in very water-rich environments, which may have been conducive to the development of living organisms in the early eras of Martian climate, the SAM team was well aware of the potential these minerals held.

Their intuition was right. In December 2014, they announced the first definitive detection of organic molecules on the Red Planet's surface – preserved between the layers of clay underneath the planet's surface.

McKay suggests that on the wish list of scientists interested in whether there is life on other worlds, there are a series of increasingly exciting possibilities for what Curiosity may be able to detect. Any organic molecules at all are attention grabbing, but some could be positively mesmerising.

For instance, among the clays there might be compounds of special biological significance, such as amino acids – among the basic building blocks of life. Some complex biologically interesting molecules like amino acids are hard to detect in the kind of gas chromatograph equipment in SAM's lab. That's where the eight remaining phials of the spilled chemical MTBSTFA come into play. (If you really want to know, its full name is N-Methyl-N-tert-butyldimethylsilyltrifluoroacetamide.) By deliberately adding that to the soil, instead of spilling it inadvertently, it would bind with amino acids and make it possible to detect them.

METHANE MYSTERY

So far in its mission, the Curiosity rover has failed to resolve one other important issue: the presence of methane in the Martian atmosphere.

Various researchers have claimed evidence for methane in observations made from Earth and from Mars-orbiting spacecraft. Even Curiosity found a signal when it took its first sniff of Martian air. It turned out to be the result of contamination, probably from Earth air initially trapped in the instrument before being flushed out. But in December 2014, a similar methane spike was observed that could not be explained away so easily.

"They're very exciting measurements," said Christopher Webster of NASA's Jet Propulsion Laboratory in Pasadena, California. "They've completely opened up the debate again on Mars methane."

The fact that the methane spiked and then disappeared again means it likely originated from a small source somewhere near the rover, as a larger plume farther away would have diffused by the time it drifted across. But that still leaves the question of whether it can be attributed to methane-producing microbes or purely geological phenomena.

"We're still stuck with the fact that methane has multiple possible sources," says Bruce Jakosky, a member of the Curiosity science team. "We don't have information yet to tell."

The SAM instrument is now doing sophisticated chemistry 255 million kilometres away

ED CAMPION/NASA/GSFC

Vital signs

Finding amino acids on Mars would still not be evidence of living organisms: they have already been found in some meteorites. Even so, discovering them or other biologically significant molecules would go a long way toward showing that, at the very least, all of the necessary ingredients for the formation of life must have been present.

But there's one more possible finding, just within the capabilities of Curiosity's instruments, that could be the most exciting of all. Living organisms have one characteristic behaviour that very clearly distinguishes their metabolic activity from any known purely chemical process. The molecules of many organic compounds and amino acids are chiral, meaning that they are not identical to their mirror image. Living organisms generally process one of the forms, but not the other.

In principle, says McKay, Curiosity has one instrument that should be able to discriminate between different chiral forms of such molecules – though that capability has not been proven in practice. If it can, we have a long wait ahead. The results will take weeks, if not months, to analyse. "The key thing is to recognise the complexity of this mission, and the slow but steady pace that is going to take place," says Squyres. "It's an exciting mission, but it unfolds in an excruciatingly slow way."

Such results could be well worth waiting for. If Curiosity were to find a collection of amino acids with one prevailing chiral form, that would be a very strong indicator that they were the products of living, breathing organisms at some time in Mars's past. It would be powerful evidence, for the first time, of life on another world. Now, that really would be one for the history books. ■

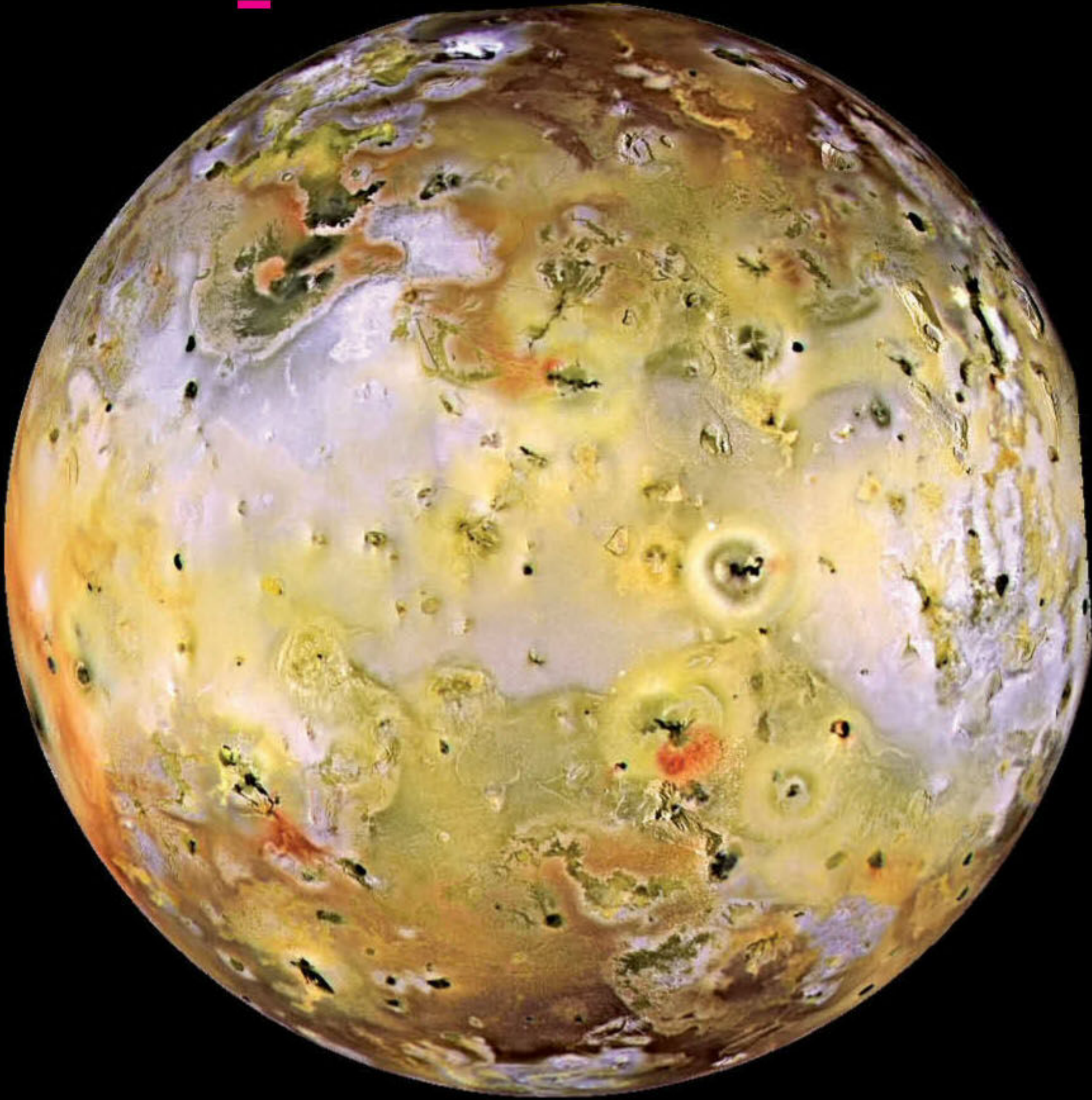
Loony moons

Moons may bow to planets in terms of size, but in character they often outshine their stolid parents.

In 2010 we celebrated four centuries since Galileo discovered Jupiter's four large satellites, at a stroke quintupling the number of moons then known to humanity. The named moons of the solar system outnumber planets by more than 20 to 1, and they display a remarkable diversity. There are fully fledged worlds such as Titan, as complex as any planet. There are possible havens for life, such as the ice-crusted water world Europa. New mysteries surround even the smallest satellites, such as the apparent flying saucers orbiting Saturn.

Join Stephen Battersby for a tour of some of the most frigid, violent and downright strange worlds we know.

THE ICY INFERNO: IO



NASA/JPL/UNIVERSITY OF ARIZONA

POCKMARKED with sulphurous pits, bathed in intense radiation and shaken by constant volcanic eruptions, Io is the fiery hell of the solar system.

Despite being cold enough to be covered in layers of sulphur dioxide frost, this large inner moon of Jupiter is the most volcanic world known, spitting out 100 times as much lava as all Earth's volcanoes can muster, from a surface area just 1⁄12th the size. Io's surface is dotted with bubbling lakes of molten rock, the largest of which, Loki Patera, is more than 200 kilometres across.

Elsewhere, magma suddenly forces its way out of fissures in the rocky crust, creating lines of lava fountains that can stretch for 50 kilometres or more. NASA's New Horizons spacecraft picked up the heat from one of these great curtains of fire in 2007 as the probe passed by Jupiter en route to Pluto.

Some of Io's eruptions are violent enough to hurl giant plumes of gas and dust 500 kilometres into space. This can happen when a lava flow vaporises the surface layers of frozen sulphur dioxide, or when dissolved gas turns to bubbles inside rising magma and blasts high-speed debris out through the moon's surface.

All this volcanic violence results from a tug of love between Jupiter and Io's two siblings, Europa and Ganymede. These moons have orbital periods exactly 2 and 4 times as long as Io's, which results in the three moons lining up every so often. Over time, the gentle gravitational tugs of this periodic conjunction have gradually nudged Io into an elliptical orbit.

As Io moves around this orbit, the grip of Jupiter's gravity weakens and strengthens, flexing the moon's rock. These stresses and strains warm the moon from within in a process called tidal heating. This effect is so powerful on Io that it can melt rock, creating the volcanoes.

Such extreme volcanism may be common in the universe. The recently discovered planet COROT-7b, for example, orbits very close to its star and so feels a very strong gravitational pull. If its orbit is only slightly elliptical, there will be enough tidal heating to plaster the planet with volcanoes. So Io may be giving us a glimpse of conditions on a million hellish exoplanets.

Io itself seems to be cooling, probably because its orbit has become less elliptical than it once was. Tens or hundreds of millions of years from now, the orbital resonance with Europa and Ganymede is likely to grow out of sync, letting Io settle into a nearly circular orbit with almost no tidal heating. Then Io's fires will finally fade.

NASA/JPL/SSI

THE WALNUT: IAPETUS

EVEN a cursory glance at Saturn's moon Iapetus reveals it to be an oddball. It is two-toned – one half is black, the other shining white – and strangely shaped, flattened at the poles and squashed at the sides as well. A ridge runs halfway around its equator, giving it the appearance of a walnut shell.

The dark stuff on Iapetus is very black indeed, but it forms only a thin veneer less than a metre thick. It covers the moon's leading hemisphere – the side that faces forward as it moves in its orbit – which suggests that the black material has been swept up from space as the moon moves around Saturn. This substance may originally have been ejected from the small, dark outer moons of Saturn during impacts with space debris.

Sunlight has sharpened the contrast on Iapetus by heating the dark areas so that any ice sublimates away. The water vapour then drifts around the moon, where it freezes on the colder trailing half, whitewashing it with a layer of frost.

The shape is harder to explain. Perhaps when the moon was young, molten and spinning rapidly, it was naturally distorted by its motion. If the outer layers of Iapetus froze solid at this time, some remnant of that shape might be preserved. But this theory can't easily account for the equatorial ridge, which remains a mystery

The ingredients of Iapetus are also peculiar. Its low density implies that it is about 80 per cent ice to only 20 per cent rock, a far lighter mixture than other large moons of the outer solar system. Any theory attempting to explain the formation of moons throughout the solar system must account for this freakish ball of ice.

LIVING SNOWBALLS: EUROPA, ENCELADUS AND TRITON

THE seemingly bleak icy surfaces of Europa, Enceladus and Triton are in fact among the most active landscapes in the solar system. They may even contain cosy habitats for living creatures.

Jupiter's moon Europa is covered by a cracked icy crust which resembles the Arctic floes of Earth. Its rocky core, however, is warmed by tidal heating, a result of the changing gravitational pull from Jupiter that arises from the moon's slightly elliptical orbit (see "Icy Inferno", page 41). This probably generates enough heat to maintain a watery ocean beneath Europa's frozen surface.

If this ocean stretches right down to the moon's core, hydrothermal vents on the dark seabed could supply nutrients that could support micro-organisms, and perhaps even shrimp-sized predators.

Saturn's snowball, Enceladus, is more violent. A set of geysers near its south pole blasts out jets of water vapour and ice crystals. Some of this tumbles back down to Enceladus's surface as snow, giving it a bright wintry coat that makes it the whitest object in the solar system. The rest escapes to form a foggy ring around Saturn.

The geysers may be rooted in an interior ocean beneath the moon's south pole. If so, traces of any microbes that might be scratching out a living there would be blasted out too, where they could be picked up by a passing probe. Life on Enceladus would be much easier to detect than any imprisoned creatures on Europa.

Living on Enceladus would be no easy ride, however. All the moon's activity is probably caused by tidal heating – unless there is something genuinely weird in there pumping out a lot of heat – and it seems that over hundreds of millions of years Enceladus wobbles in and out of its eccentric orbit, putting it in an uncomfortable cycle of climate change. Life would be doomed if the sea freezes completely during the coldest epochs.

Even chilly Europa and Enceladus, with mean surface temperatures of around 100 K and 75 K, are balmy paradises compared with Neptune's largest moon, Triton, where the temperature hovers around 40 K (below -230 °C). Triton's surface is frosted with various exotic ices, including blends of water, nitrogen and methane.

And yet this frozen world is surprisingly lively. Geysers erupt when sunlight evaporates volatile deposits of nitrogen, and a thin atmosphere of nitrogen holds tenuous clouds in weather

NASA/JPL/SSI

FLYING SAUCERS: PAN AND ATLAS

MOST moons are either round and smooth, or lumpy pieces of space rock. Saturn's Pan and Atlas, on the other hand, come straight from the set of a 1950s B-movie. With a central bulge set inside a disc-like ridge, they bear an uncanny resemblance to your stereotypical flying saucers. Atlas, the flatter of the two, has a diameter of only 18 kilometres from pole to pole, but is almost 40 kilometres across its waist.

Their strange shape is something of a mystery. While the moons' rapid rotation would be enough to squash them into a smooth oval it can't explain the rim around the centre of the saucer shape.

A clue may lie in the moons' orbits, which lie very close to Saturn's rings. Perhaps icy material from the rings fell onto them, piling up near the equator to form the ridges. That would fit with observations that the ridges are very smooth compared with the rugged polar regions, implying they are made from fine particles similar to those found in Saturn's rings.

This theory is far from proven, however, and new observations may eventually explain the flying saucers of Saturn. We can probably rule out alien technology, though.

THE BOOMERANG: NEREID

WHILE most moons gently circle their planets, Nereid swoops vertiginously. This otherwise undistinguished satellite of Neptune, moderately lumpy and middling in size, travels on the most eccentric orbit of any moon in the solar system – a roller-coaster ride that takes it soaring out more than 9 million kilometres from the planet, and then plunging back to within 1.4 million kilometres of it.

Most moons with irregular orbits are thought to be former comets or asteroids captured by their parent planet's gravity, and that may be Nereid's story too. But its composition does not resemble that of the other loose objects in the Kuiper belt, the area of the outer solar system that would most likely have been its original home. Instead, it probably formed from the disc of leftover material that once orbited Neptune. Such moons normally follow a circular orbit around their planet, however, leaving Nereid's rogue path a mystery.

The answer could come from Nereid's step-brother, Triton. This giant moon orbits Neptune in the opposite direction to Neptune's own rotation, raising the possibility that it came from elsewhere and was captured by Neptune's gravity (see "Living Snowballs", below). That event could have thrown most of Neptune's original clutch of moons completely out of the system, and sent Nereid on its wild ride.

patterns that change with Triton's seasons.

Like Europa and Enceladus, Triton has a flat landscape with very few impact craters. Such a smooth complexion implies that the surface is very young – probably less than 10 million years old, a tiny fraction of the moon's 4-billion-year age. Triton's fountains of youth are thought to be volcanoes that erupt a cold lava of water and liquid ammonia, freezing to cover the surface with fresh ice and erase the signs of age.

Triton may once have been a dwarf planet like Pluto, orbiting the sun independently of Neptune. Indeed, Triton is about the same size as Pluto and has a similar composition, suggesting a similar origin. But the clincher is that it orbits Neptune backwards, in the opposite direction to Neptune's rotation, impossible if it formed from the same rotating cloud of gas and dust as its planet. Instead, Triton was probably captured by Neptune.

Capturing such a large object is no mean feat. It may be that Triton smashed into an existing moon of Neptune, which slowed it down sufficiently for the planet's gravity to snare it. A more likely theory is that it started life in a binary pair of dwarf planets, one of which was flung away at high speed when the pair encountered Neptune's gravity, leaving Triton behind.

As well as being a remarkable moon in its own right, Triton may be giving us a hazy picture of the unexplored dwarf planets beyond Pluto – such as Eris, Makemake, Haumea and probably dozens more that wander in the outer darkness of the solar system.

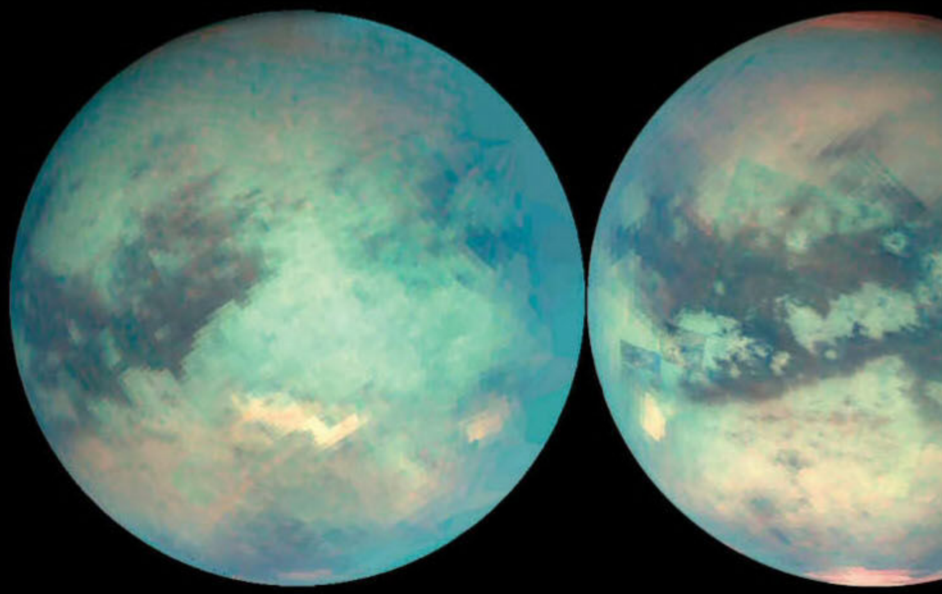
NASA

SECOND EARTH: TITAN

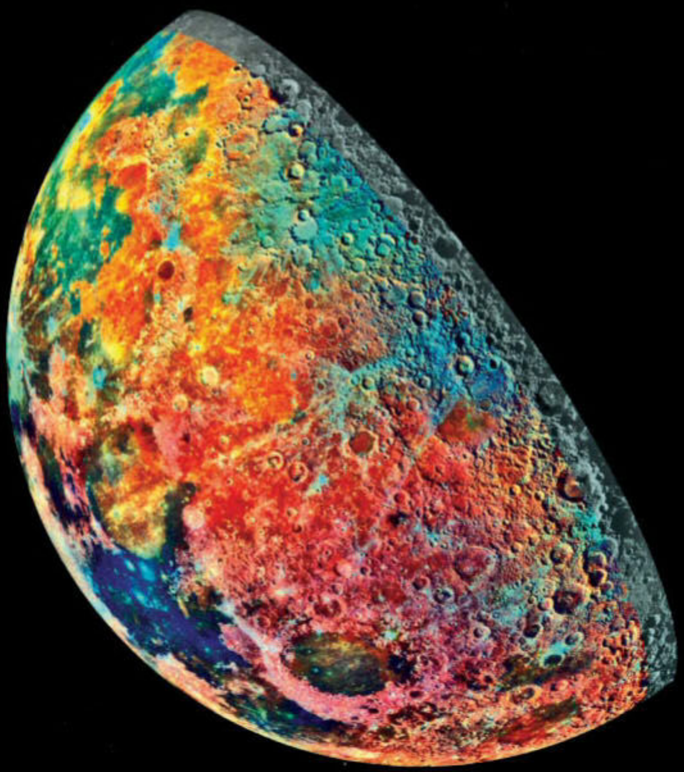
IT IS perhaps the strangest of all moons because it is so eerily familiar. The newly revealed face of Titan has the same weather-beaten features as Earth: lakes, hills and caves; branching river valleys; muddy plains and desert dunes. The thick nitrogen atmosphere holds fog, mist, smoggy haze and rain clouds. As one scientist commented when the first images came back from the Huygens probe in 2005, it looks just like England.

Looks can be deceiving, though. Titan circles Saturn, 10 times as far from the sun as Earth is. Under such feeble sunlight its surface only reaches a high of -180 °C. Any water forms ice that is hard enough to be carved into mountain ranges.

The rain, rivers and lakes seen by Huygens are actually liquid hydrocarbons that would be gases at Earth temperatures. Estimates suggest the lakes are made of 80 per cent ethane, with slugs of propane, methane and acetylene, which some researchers believe could be a source of food for Titanian life (see "Splash of the titans", page 47).



THE ORIGINAL AND BEST: THE MOON



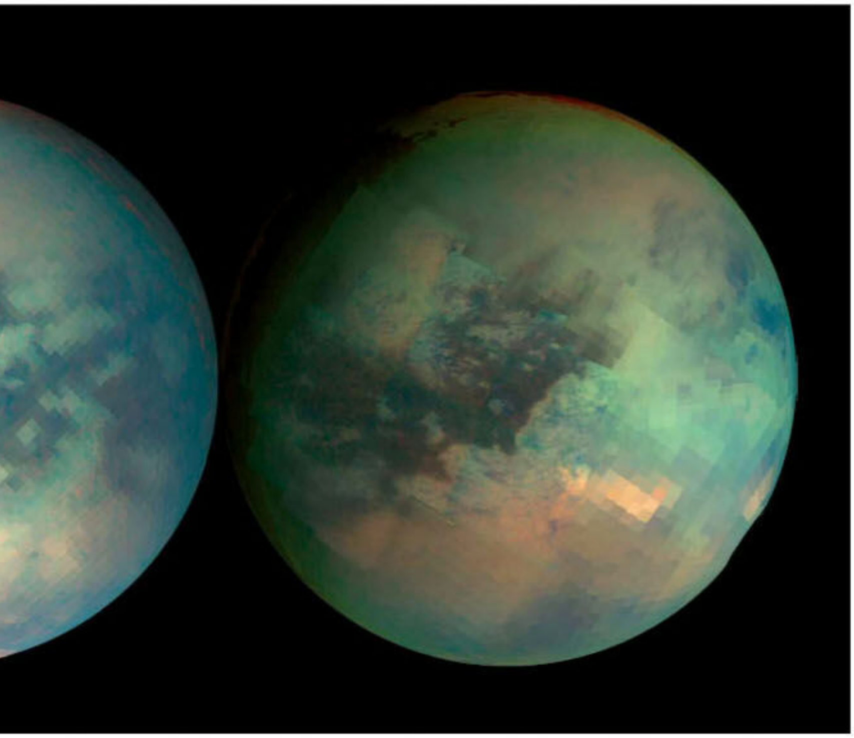
NASA/JPL

UNTIL Simon Marius and Galileo Galilei discovered four of Jupiter's moons over 400 years ago, the only known moon was a rather prominent object in Earth's night sky – one that is familiar even to today's light-blighted city dwellers. Since then, scores of moons have been discovered within our solar system, yet Earth's companion still stands out as one of the most remarkable members of this clan.

For one thing, it is a very big fish in a small pond. Moons are rare in the inner solar system: Venus and Mercury don't have any, and Mars's two moons are tiny pebbles in comparison with ours. Indeed, our moon would seem more at home in the outer solar system, among the massive satellites that orbit the gas giants.

The moon's bulky dimensions may be a reflection of its unique origin. Moons are generally thought to form in one of two ways – either by coalescing from the same cloud of debris as their parent planet, or as wandering objects captured by the parent's gravitational pull. Our moon had a more bloody birth, when a large protoplanet collided with the young Earth 4.5 billion years ago and cast out a glowing ring of melted and vaporised rock, some of which condensed to form our satellite. That ancient cataclysm might have been lucky for us, as the moon helps to stabilise the axial tilt of Earth, removing one source of extreme climate change that might otherwise have afflicted our planet.

It looks as though the US has abandoned crewed missions to the moon for the foreseeable future. The long-term prospects for human colonisation were nonetheless given a boost in 2009, when NASA's spacecraft LCROSS found the firmest evidence yet for water ice buried at the lunar south pole.



NASA/JPL/UNIVERSITY OF ARIZONA

OUT OF THIS SOLAR SYSTEM: EXOMOONS

IF OUR solar system holds so many remarkable moons, then what strange satellite worlds might we find among the billions of planetary systems in the Milky Way? Perhaps there are temperate, habitable moons orbiting some giant exoplanets. We shouldn't expect to find them inhabited by intelligent life such as the furry Ewoks of Endor in *Star Wars*, but such moons may be among the most likely habitats for life in the universe (see "Home, sweet exomoon", page 98).

On the face of it, detecting a moon around a planet orbiting a distant star seems like a spectacularly difficult task, but with a bit of luck today's technology may be able to do it. The best approach is to look for transits, in which an orbiting planet passes in front of its star, dimming the amount of light we detect on Earth. This method has already been used to find several planets, and it could indirectly reveal exomoons. As a moon orbits a planet, its gravity makes the planet move, changing the timing and duration of transits.

The bigger the moon in relation to the planet, the bigger this effect. In one simulation, a planet with the mass of Neptune situated in the habitable zone of a star – not too hot, not too cold – was given a moon the size of Earth. This weighty moon would change the timing and duration of its planet's transits enough to be detectable by the Kepler planet-finding satellite, or even by ground-based telescopes. Such a large moon would also be able to hold onto a thick atmosphere, making it a prime spot for life.

"Titan has the same weather-beaten features as Earth: lakes, hills, muddy plains and desert dunes"

AND THE REST...

WHICH IS THE LARGEST MOON?

Jupiter's moon Ganymede, with a diameter of 5270 kilometres, is larger than the planet Mercury and has a volume three times as large as our moon. It is the only moon to have a strong magnetic field of its own, which suggests that it has a convecting core of liquid metal.

HOW MANY MOONS ARE IN THE SOLAR SYSTEM?

At the time of going to press, more than 170 have been named. The true total depends on where you draw the line, though. There is as yet no definition of the minimum size an object has to attain to be classified as a moon, so if you are happy to give the label "moon" to any piece of solid matter orbiting a planet – including every ice crystal in the rings of Saturn – then the number could run into quadrillions.

HOW MANY MOONS DOES EARTH HAVE?

One. No surprises there. But another object discovered in 1986 is sometimes, rather fancifully, called Earth's second moon. The 5-kilometre-wide asteroid Cruithne orbits the sun in an elliptical orbit that is locked in a complex resonance with the Earth, making periodic and predictable close approaches.

WHICH MOON WAS NEARLY UPGRADED TO PLANET?

Charon, the satellite of Pluto. According to a draft definition of the term planet that was presented for approval at a meeting of the International Astronomical Union in Prague, Czech Republic, in 2006, Charon would have met both qualifications for planethood. It is big enough for gravity to pull it into a rounded shape, and in a sense it orbits the sun directly: Charon and Pluto circle a common centre of gravity which is actually in empty space between the two bodies. If this definition had been approved, the two would have been called a binary pair of planets. As it is, it was Pluto that was downgraded, giving us a mere moon orbiting a humble dwarf planet.

DO ANY MOONS HAVE MOONS?

Not in our solar system. It is possible for a moon to orbit a moon, but the fluctuating gravitational forces exerted by the planet and the mother moon will make the orbit unstable in the long run. On large enough scales a moon's moon might last billions of years – after all, the planets orbit the sun and they can hold onto moons – but none has lasted in our solar system.

Some asteroids have moons, such as Ida and its satellite Dactyl. And during the past half-century Earth's moon has had a few short-lived satellites. Their composition was mainly metal, with a small percentage of human in some cases.

Splash of the Titans

Methane tides, an icy seashore and the strangest whirlpool in the solar system. **Stephen Battersby** welcomes you to Saturn's largest moon

THE sky is a baleful orange, but then it's always like that. The roar of the approaching maelstrom is new though, and disturbing. As are the gathering clouds, which threaten to loose a deluge more violent than anything ever seen on Earth. A sailor on an alien sea may hesitate: is it wise to venture into the Throat of Kraken?

One day this could be a real scene on Saturn's giant moon, Titan. Apart from Earth, Titan is the only world known to have liquid on its surface. We first glimpsed its alien lakes and seas through the eyes of the Cassini spacecraft in 2006. Now, after ten years of slow exploration, Cassini is unleashing a flood of remarkable discoveries. A view of the sea floor, previously thought impossible. A puzzling chemical make-up. Signs of waves that herald a coming storm. And there, in the heart of Kraken Mare, an archipelago of islands that pinch the sea almost in two to form a perilous strait where, just maybe, a monster may be hiding.

If so, what the monster swallows isn't water. While rivers of water run through mountains of rock on Earth, on Titan the streams are liquid methane and the hills and plains are made of water ice. Long before the Cassini mission arrived, scientists had calculated that methane and other liquid hydrocarbons might collect into seas – perhaps even forming a global ocean. Nobody could be sure, though, because an orange layer of smog hides the moon's surface. So Cassini carried a lander called Huygens that was designed to float.

When Huygens did plunge through the smog in 2005, it sent back images of an eerily Earth-like landscape that revealed its landing site was a pebbly mudflat. The ground was soaked with methane, but it was hardly the hoped-for ocean.

More than a decade on Cassini is still exploring Saturn and its moons, flying by Titan from time to time. Infrared cameras provide a hazy view of the surface. Radar can cut through the smog to give a sharper image, but it can only map a narrow slice of the moon on each fly-by. So the big picture has been building at a tantalisingly slow pace.

The first clear sight of lakes came in 2006, when radar showed dark patches in the northern hemisphere occupying depressions in the landscape. While the picture was sketchy, it seemed that one of these liquid bodies was more than 1000 kilometres long, large enough to be considered a sea. It was named Kraken Mare, after the monster of Norse legend. Since then two more seas have been identified, along with dozens of lakes.

Then in 2013, Cassini caught a glimpse of something that scientists thought was impossible. On 23 May, the spacecraft flew low over Ligeia Mare, the second sea of Titan. Its radar was aimed straight down, enabling the instrument to trace out the height of land and sea by sending out sharp pulses of radio waves, then measuring how long it took for the reflections to ping back.

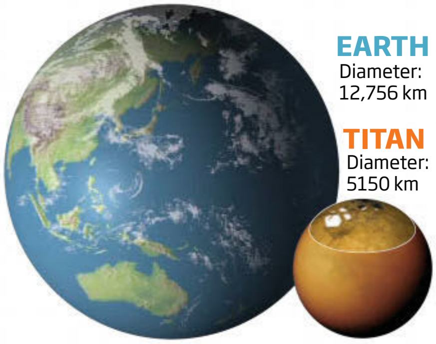
When the team first looked at the data there was just a single ping from the sea surface, as expected. But Marco Mastrogiuseppe, then at the Sapienza University of Rome in Italy cleaned up the raw data using an algorithm he had developed for the radar on the Mars Express spacecraft. He then saw a second faint ping, not much more than a microsecond after the first, bouncing off the seabed.

"I was on the bus to Rome when I discovered the bottom of Ligeia Mare," he says. "I was so excited that I was talking about it to the guy sitting next to me. He thought I was crazy."

This is the first time we have plumbed the depths of any sea or lake beyond Earth. The timing of the second reflection shows that Ligeia Mare is about 160 metres deep.

It comes as a huge surprise that the seabed can be seen at all. That is because Titan's atmosphere is choked with complex hydrocarbon molecules that absorb radar, and everyone assumed that some of these would muddy the seas. "We thought it would be impossible to see to the bottom," says Alex

Worlds together



A TITANIC VOYAGE

Bays and beaches a billion kilometres from Earth; a fine view of Saturn's rings rising above the waves and whirlpools; an exotic chemistry that could illuminate the origins of life. Titan could hardly be a more alluring destination. Surely we should be launching a boat to explore its distant shores?

Hunter Waite wants to go a step further and send a submarine. "It wouldn't be much harder to build than a boat," he says. At the Southwest Research Institute in San Antonio, Texas, Waite developed a mission concept in 2010. His floating mothership holds a submersible that would dive down by letting methane flood a hollow chamber. Later the sub can discard the chamber and ascend to the surface again.

The latest results from Cassini's radar may make this even more desirable. Titan's atmosphere is clogged with a smog of complex organic molecules, which ought to be washed into the seas when the rains fall, yet the seas seem to be clear (see main story). "It might imply there are organic sediments at the bottom of the sea," says Waite.

Those sediments may hold chemical treasure – especially if liquid water from Titan's interior is seeping out down there, mimicking the oxygen-free, organic-rich environment of the early Earth. A submarine could also measure the isotopic mix of various chemicals, to help geologists learn how Titan formed and evolved.

Time is running out for a trip before the next northern winter draws in. With the seas in darkness and hidden from Earth, a mission would be more difficult and less rewarding.

Hayes of Cornell University in New York.

So see-through Ligeia must be free from those complex hydrocarbons. Some blend of ethane and methane seemed to be the most likely option. And because methane should evaporate quite rapidly from the seas, planetary scientists expected lingering ethane to dominate.

Again this strange moon surprised everyone. This time the discovery came in a lab on Earth. Karl Mitchell and his team at the Jet Propulsion Laboratory in Pasadena blasted samples of ethane and methane with radio waves close in frequency to that of Cassini's radar. They found that ethane absorbs the radio waves too strongly to fit the seabed sighting from Titan. So Ligeia seems to be mainly filled with liquid methane. "That has turned everything on its side," says Hayes. Something must be refreshing the northern seas with crystal-clear methane.

That single track traced across Ligeia has now opened a much wider view of Titan's undersea realms. When Hayes and Ralph Lorenz, then at the University of Arizona in Tucson, heard of Mastrogiuseppe's finding, they realised that Cassini might have been seeing through the seas all the time. "We invited him to coffee next morning and locked him in a conference room until he explained how he got his result," says Hayes.

Seaside like no other

When the radar is in imaging rather than depth-sensing mode, it points slightly to one side and rakes a broad beam across the moon's surface. Dry land generally looks bright, as its rough surface reflects some of the beam back, while smooth lakes look dark. But there has always been a residual trace of backscatter from the lakes – which turned out to be a ghostly picture of the seabed.

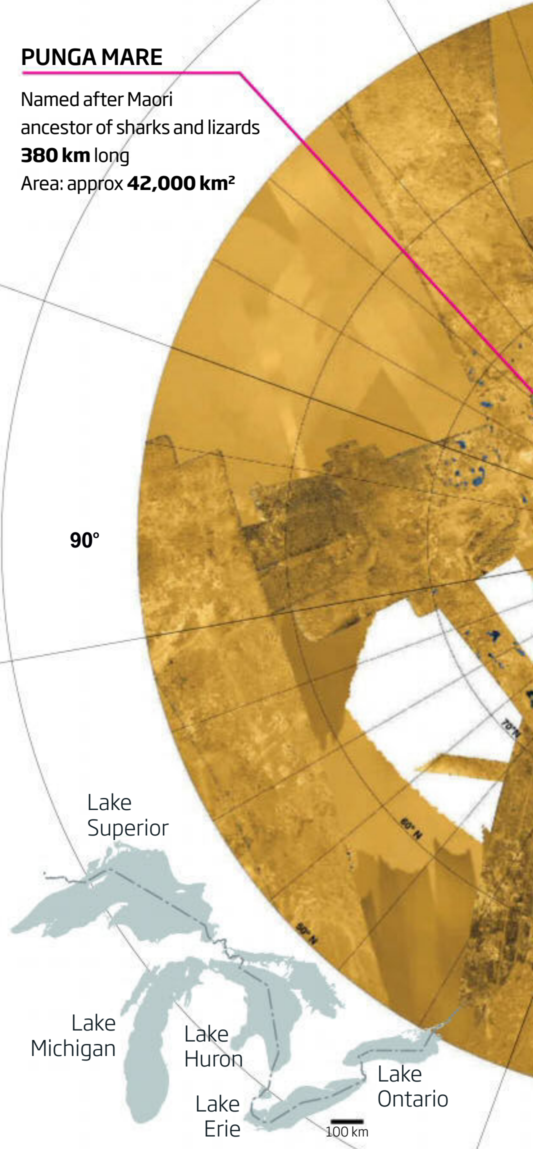
The Ligeia findings gave Hayes and his colleagues the vital information needed to develop this picture and print a preliminary map of the northern seabeds. With this, they worked out that the total volume of Titan's seas came to 70,000 cubic kilometres, or 55 times the volume of proven oil reserves on Earth.

This analysis assumes that the other seas have the same composition and seabed characteristics as Ligeia. Following a Cassini fly-by over Kraken Mare in August 2014, such an assumption appears to be justified – although the sea's great depth unfortunately made direct observation of the seabed impossible.

As the largest alien sea, Kraken Mare holds a particular fascination, and most plans for a maritime mission to Titan have targeted it (see "A Titanic voyage", left). Now the Kraken's shorelines have been fully charted with indirect help from a shift in the seasons.

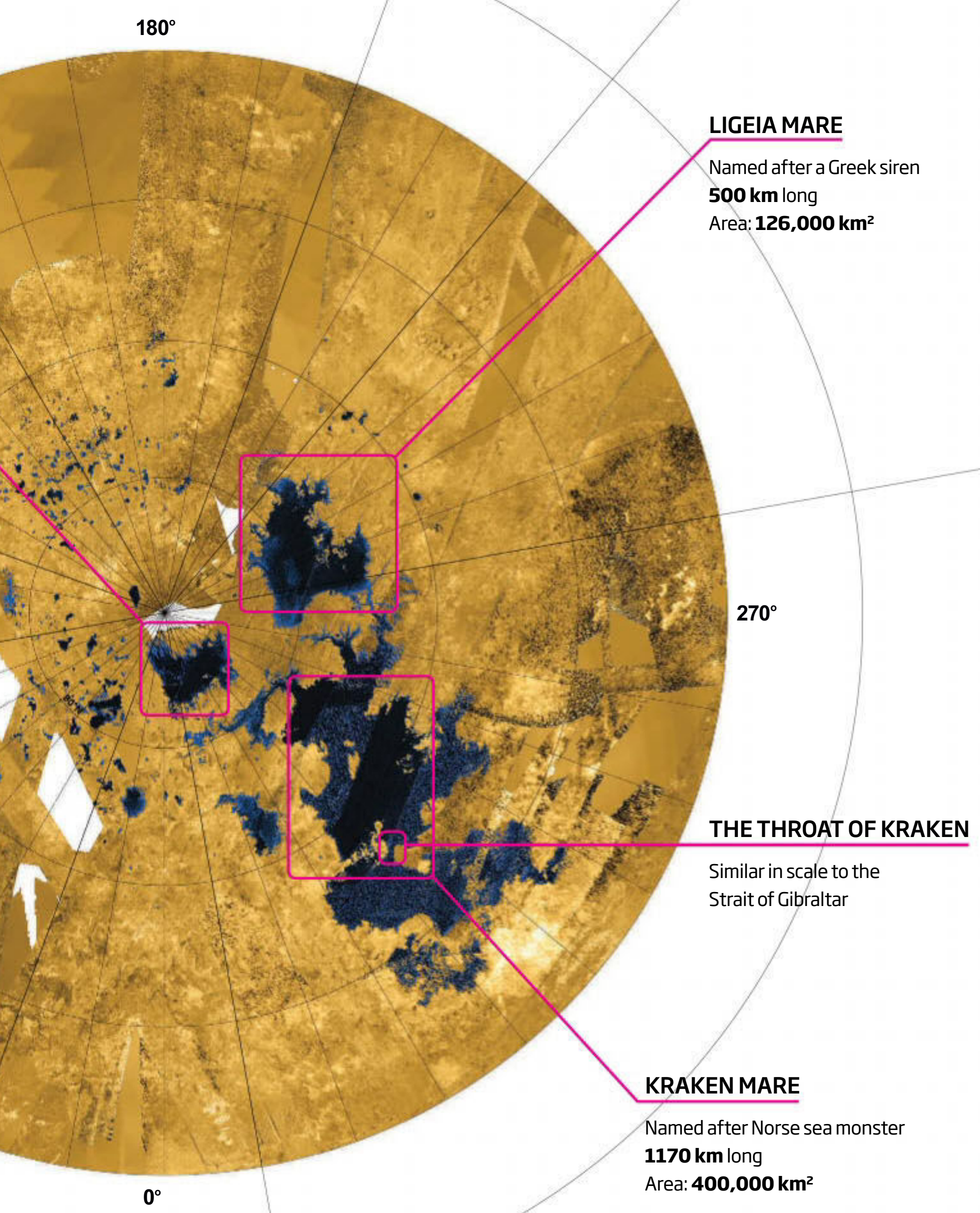
Titan's journey around the sun takes about 29 Earth years, and since 2004 Cassini has witnessed the end of the southern summer, an equinox and now springtime in the north. As light creeps across the land, Cassini has been steered over the northern hemisphere more often so that its cameras can take advantage. This, too, has given the radar more opportunities to map the lakes. And a new map was presented by Hayes, Lorenz and others at the Lunar and Planetary Sciences Conference in Houston in 2014.

It showed that Kraken Mare is cut almost in two by promontories of land and a string of islands. Lorenz named this feature the Throat of Kraken. "It did cross my mind that 'sphincter' would be anatomically descriptive," says Lorenz, "but that didn't have quite the same charm."



He realised that something special might be going on at this maritime divide. The gravity of Saturn is expected to cause tides in the seas of Titan. As the moon follows its orbit, the tide should rise and fall in Kraken Mare by around a metre. As it rises in the north it should ebb in the south – flowing from one end of the sea to the other, funnelled through the Throat.

There, the tidal current could reach speeds of 2 kilometres per hour, according to Lorenz's calculations. While that is only strolling pace to us, on Titan things are different. Gravity is much lower than on Earth and the liquid in the seas is much lighter. So the tidal current may be brisk enough to send the Kraken into a



frenzy. Lorenz likens the Throat to the west coast of Scotland, where two islands frame the Strait of Corryvreckan. Tidal currents here churn the sea surface into a maelstrom, with one of the largest whirlpools in the world. The Corryvreckan can be heard miles away.

Could the Kraken host a whirlpool too? If so it would be a curious coincidence, as legend tells that the monster after which the sea is named would create whirlpools to drag sailors to their doom.

The Corryvreckan and other whirlpools depend on the positioning of subsurface rocks as well as the fast flow of fluid, so a tidal race on Titan may not create such mayhem. But a future mission to the seas of Titan should listen out, Lorenz suggests. Perhaps it will hear the Throat of Kraken roar.

Apart from the tides, a dead calm seems to prevail on Titan's seas today. The radar results show that Ligeia Mare is smooth as silk, with no more than a millimetre variation in height. The uniform blackness of the other seas suggests that they, too, are flat. "You could see your face in them," says Hunter Waite of the Southwest Research Institute in San Antonio, Texas. These are true seas of tranquillity – with one possible exception. A radar sweep in 2012 over Punga Mare, the smallest of Titan's three seas, revealed four suggestive glints that could be reflections from waves, according to Jason Barnes at the University of Idaho and his colleagues. These waves would only be a couple of centimetres high, but they may herald a season of storms.

"A future mission to the seas of Titan might hear the Throat of Kraken roar"

The seas are so smooth today because winds are gentle. Blowing at no more than 0.5 metres per second, the wind can't raise even a ripple. Now with summer approaching, models of Titan's climate predict that wind speeds could rise to 2 metres per second or so. Even that is just a light breeze on Earth, barely enough to create ripples, but remember that the low gravity and light liquids make Titan's seas more sensitive. The atmosphere is much denser, giving the wind more force. A wind of 2 metres per second could generate waves around a metre high. Where these reach the shallows they may grow much taller, perhaps enough to tempt future surfers.

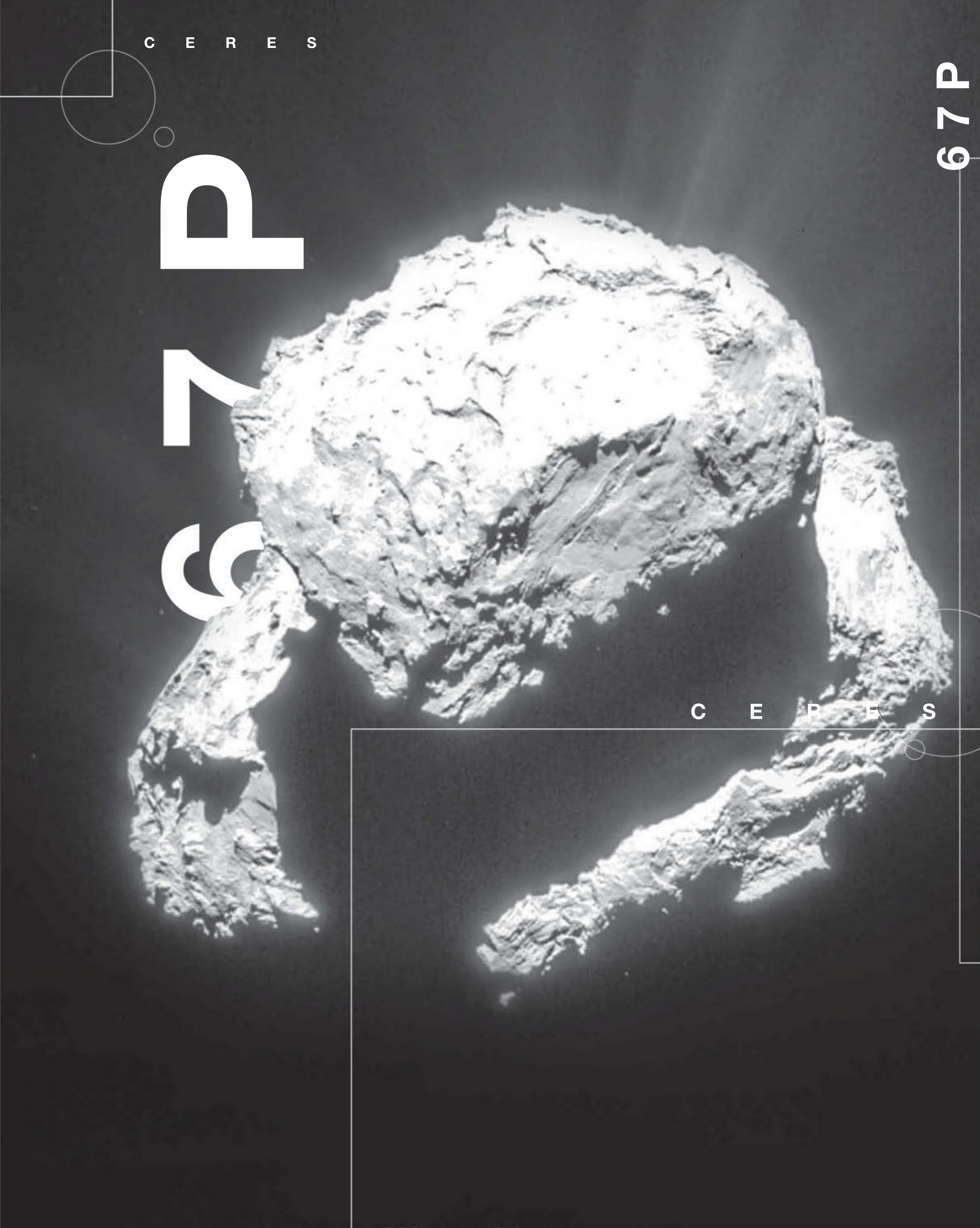
Far more extreme winds are predicted by Tetsuya Tokano of the University of Cologne in Germany. He calculates that something akin to tropical cyclones could form, with winds of up to 20 metres per second. His conclusion assumes that the seas are filled with volatile methane – just as the radar observations imply. But Lorenz is doubtful. "I can't say it won't ever happen, but so far we haven't seen a cyclone on Titan."

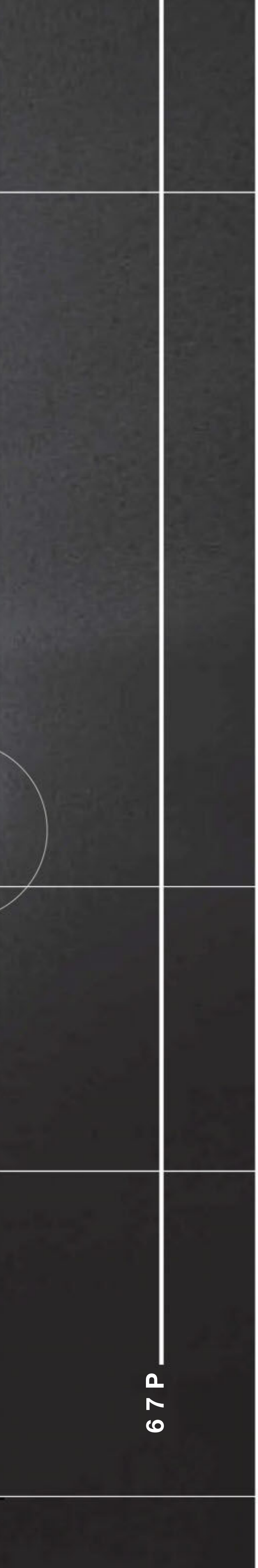
A stunning storm of a different kind is widely expected, born of Titan's dense, brooding atmosphere. While Earth's air can hold enough water vapour at one time to sprinkle the entire planet in a couple of centimetres of rain, Titan's carries enough methane to cover the moon in several metres of liquid. Any given spot may be dry for centuries, then suddenly see all that moisture come crashing down in a matter of hours.

Cassini caught a glimpse of cloud in the south just after it arrived at Saturn, marking the tail end of the last rainy season, and has seen new clouds form more recently as well. Climate models predict that the northern rains are due to start in the next couple of years, says Lorenz. "It could be that as we speak, the biggest rainstorm in recorded history is erupting over Titan."

If so, it will help to refresh the crystal-clear liquid of the northern seas, and perhaps even fill new lakes or inlets. Studying Titan's storm clouds might also tell us something of our own planet. "Titan is a great lab for processes that happen on Earth, and clouds are the biggest uncertainty in climate models," says Lorenz. Titan's starkly alien conditions might test the power and flexibility of those models.

For now, Cassini is on watch, looping around the Saturn system, periodically swooping down on Titan. Scanning the seas. Waiting, waiting, until the Kraken wakes. ■


CERES
67P
67P
CERES



Water, water everywhere

Where did Earth get its life-giving liquid? Rosetta's Philae lander that touched down on comet 67P in November 2014 has left us facing a mystery, says **Stuart Clark**

ROSETTA'S TIMELINE

MARCH 2004
Mission launched from French Guiana

MARCH 2005
First Earth flyby provides a gravitational slingshot towards comet 67P

FEBRUARY 2007
Low altitude flyby of Mars

NOVEMBER 2007
Second Earth flyby. Rosetta is mistakenly identified as a near-Earth asteroid and given the name 2007 VN84

SEPTEMBER 2008
Rosetta passes through the main asteroid belt

NOVEMBER 2009
Rosetta passes within 2500 km of Earth on its third and closest flyby

JUNE 2011
Rosetta starts deep-space "hibernation" with most electronics switched off

JANUARY 2014
Rosetta woken up from deep-space slumber and resumes communication with Earth

AUGUST 2014
Rosetta arrives at comet 67P and begins to map viable landing locations from 100km away

NOVEMBER 2014
The lander Philae touches down bumpily on the comet's surface. Harpoons to tether the craft to the surface fail to fire

MARCH 2015
Attempts to contact Philae to see whether its solar batteries have recharged as the comet nears the sun

JULY 2015
The comet's distance from the sun is such that the lander's temperature drops below its operational limit

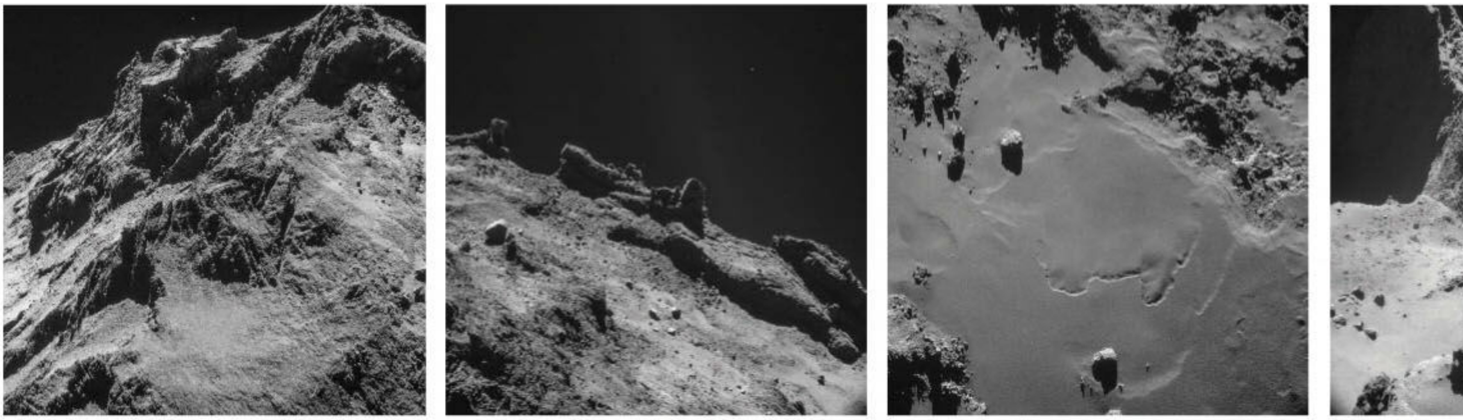
COMET might be the proper term, but "dirty snowball" would be more descriptive. Travelling in large, elliptical orbits that periodically bring them from the solar system's outer reaches to its inner regions, these mountain-sized lumps of ice and rock boil off when bathed in the sun's rays, giving rise to their trademark tails.

The wonder – and fear – these cosmic wanderers have inspired over centuries is reason enough to seek a closer encounter. But comets are also windows on the solar system's ancient past, being bits left over from the formation of the planets billions of years ago. So planetary scientists were expecting a treasure trove of information when, in 2014, the Rosetta mission beamed back its first data from 510 million kilometres away, as it arrived at the comet 67P Churyumov-Gerasimenko.

They haven't been disappointed. The mission has revealed that the comet, unexpectedly, has almost no magnetic field, while some of its surface features seem to have been formed by wind. But most intriguing is what has emerged about the water 67P contains – and what that might mean for how Earth itself became wet.

Comets have long been crucial for explaining Earth's water. In our planet's early days, water would just have boiled away from its hot ›

"It seems comets can't have been the source of Earth's water. So what was?"



surface. To get around this problem, a well-established theory is that our planet received an express delivery of life's vital solvent later on, when it was bombarded by icy bodies like comets. Although atmospheric weathering and tectonic activity have erased obvious evidence from Earth, the moon's cratered face tells us that such bombardments did happen during the solar system's convulsive early aeons. This cometary ice also contained carbon-rich molecules, supplying Earth with a starter pack for life, freeze-dried for freshness.

But that's not the story Rosetta tells. "Even before we did any analysis we could see that the cometary water was completely different from the Earth water," says Kathrin Altwegg of the University of Bern in Switzerland. She is in charge of Rosetta's ROSINA instrument, which scrutinised the water it encountered when passing through 67P's tail.

Ordinary water is made of two hydrogen atoms bound to an oxygen atom. But just occasionally, one or both of those hydrogens is replaced by deuterium, a stable isotope of hydrogen with an extra neutron in its nucleus. On Earth, there are roughly 160 molecules of this "heavy water" for every million ordinary molecules, a number known as the D/H ratio.

The D/H ratio of 67P was triple that of Earth – confirming a discrepancy that has been in the air a while. In 1986, Altwegg was a young researcher on the European Space Agency's Giotto mission when it rendezvoused with and photographed Halley's comet. Indirect spectroscopic measurements suggested Halley's D/H ratio was twice Earth's. Similar studies of around a dozen comets since have indicated something similar: only one, named Hartley 2, contains water with a similar D/H ratio to Earth's oceans.

That would seem to indicate comets weren't the source of Earth's water. So what was?

Asteroids are one alternative – one that had long been ruled out. The closest, brightest of these bodies, which orbit in a belt between Mars and Jupiter, are bone dry. And while some meteorites found on Earth, which are thought to have been flung from more distant members of the asteroid belt, do contain water with the right D/H ratio, there isn't nearly enough to supply Earth's oceans.

At least that was the view when Laurence O'Rourke, Rosetta's science operations coordinator, started using another of ESA's missions, the infrared space observatory Herschel, to look for water on asteroids. Specifically, he was targeting the largest of the asteroids, Ceres, some 1000 kilometres in diameter and now classed as a dwarf planet.

Ceres orbits in the middle of the asteroid belt, following an elliptical path that varies in distance from the sun from about 2.6 to 3 astronomical units (1 AU is the distance of Earth from the sun). This crucial region straddles the solar system's snow line, the boundary beyond which the sun's rays are so weak that any water condenses to ice crystals.

"Ceres is in this really special place, where ice was starting to become a major planet-building material. As you went further from the sun, you got more and more ice crystallising," says Britney Schmidt, a planetary scientist at the Georgia Institute of

ASTEROID AHOY!

The arrival of NASA's Dawn mission at Ceres has already excited interest in this dwarf planet and largest of the asteroids.

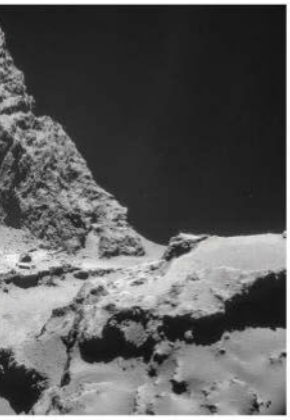
The way the Dawn spacecraft bobs around while orbiting Ceres will tell us about the dwarf planet's internal structure, helping to determine its density and exactly what fraction of ice it contains. It should also help explain its mysterious bright spots, thought to be salt deposits reflecting incoming light.

Meanwhile, three instruments will investigate the crucial question of its water content directly. Its camera will check for surface ice deposits, or other features shaped by past ice. Its spectrometer should see telltale frequencies of infrared light given off by water locked inside surface minerals, and also reveal organic material if it is there. Finally, its neutron detector will look for the effect of water ice on and just below the surface on the emission of neutrons from the surrounding rocks – a technique successfully used on the moon and Mars.

NASA is not the only space agency with its sights set on the asteroids. In 2014, the Japanese space agency JAXA launched Hayabusa 2, which is due to arrive at the unassumingly named 1999 JU3 in 2018. In addition to mapping and spectroscopic observations, it will descend to the surface and collect samples, returning them to Earth in 2020 if all goes well.

"C-type" asteroids such as 1999 JU3 are thought to be the parent bodies of a rare type of meteorite, the carbonaceous chondrites. These are distinguished by their dark colour and an abundance of organic molecules, and those found on Earth display all the hallmarks of having been formed in the presence of water.

In short, they – and perhaps their parent bodies – seem to have all the ingredients needed to fill the oceans and spark life on Earth.



Rosetta has delivered the most detailed picture of a cometary surface yet

Technology in Atlanta. With a density around 2000 kilograms per cubic metre that is neatly in between that of ice and rock, Ceres, and its more distant asteroid siblings generally, could plausibly be half rock and half ice. Such asteroids could have supplied significant amounts of water to the early Earth.

Sadly, O'Rourke's first measurements in November 2011 revealed a disappointingly desiccated body. It was a different story when he looked again in October 2012. "We got a very strong detection of water," he says – the first confirmed detection of water in the asteroid belt.

What had changed was Ceres's position. In 11 months, its orbit had taken it from 3 AU to 2.7 AU from the sun, enough to come within the snowline and turn some of its ice to vapour. About 6 kilograms of water was being released every second, surrounding the asteroid in a tenuous atmosphere rather like a comet's. In fact if comets are dirty snowballs, asteroids such as Ceres look increasingly like they might be snowy dirt balls.

NASA's Dawn mission, which was captured by Ceres's gravity on 6 March 2015 to begin a 16-month study of the dwarf planet, is one probe that could provide more clues to its composition (see "Asteroid ahoy!", left). But regardless of what Dawn finds, it's unlikely to be as simple a picture as one in which bombardment by material from asteroids, rather than comets, brings water and organic molecules to Earth. "That can't be the whole story," says Ian Wright of the Open University in the UK.

The reason is written once again in the moon's cratered face. Most models of the solar system's evolution involve the giant planets – Jupiter, Saturn, Uranus and Neptune – migrating closer or farther away from the sun before settling into their final orbits. These movements would have upset comets' orbits, throwing some into the inner solar system.

So there must be at least some cometary water with its heavy make-up mixed into Earth's oceans. "It's like paint, you mix red and yellow and you get orange. So, if you have a component that's three times 'heavier' than Earth water and a component that's three times 'lighter' and you mixed them 50:50, you'd get Earth water," says Wright.

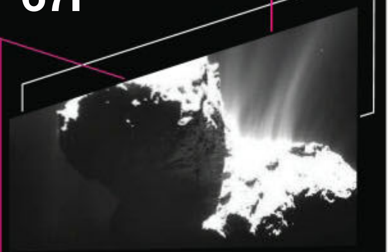
The answer to where that lighter component might come from might lie in our still-emerging understanding of the solar system's "water cycle": a sequence of events that began when the sun and the planets were nothing more than a frigid mixture of gases drifting through space. In these interstellar clouds, atoms occasionally stick together and form molecules. By a quirk of chemistry, the isotopic composition of any water formed depends on temperature: the colder it is, the more deuterium it ends up containing. Interstellar clouds are typically at a frigid -220° C to -260° C, which will yield D/H ratios at least three times those on Earth.

But under the warming influence of the nascent sun, some water molecules would have been broken up and reformed, lowering the D/H ratio as they did so. So in all probability bodies formed across the solar system with a huge range of D/H ratios, as indeed the observations of comets so far suggest – and Earth got bombarded with a selection of them all. That, combined with some moisture baked out of our planet's interior by a process known as outgassing, might have supplied the right sort of water. The fit is still not perfect: bodies with a Ceres-like distance are likely to have lower D/H ratios, but models show that making asteroids with exactly the right low D/H ratio takes too long.

Whatever the full story, the tale of the wrong water does shed new light on comet 67P itself. Its extraordinarily high D/H ratio suggests we have, more by luck than judgement, stumbled on a body that has more claim than most to represent the pristine material that made the solar system – its water is, in Altwegg's words, "more or less purely interstellar".

By now, Philae's internal temperature is too low for the lander to be operational, rendering the comet's surface out of bounds once more. But it's all the more reason to regard these bodies with awe and wonder. "The beauty about studying a comet is that the stuff that has been there for 4.5 billion years," says Wright. "You warm it up and you can basically say that's the stuff that was on the surface of the Earth. I think that is fantastic." ■

67P



67P/Churyumov-Gerasimenko

Discovered: ***1969***

Classification: ***Comet***

Home: ***Solar system wanderer, between 190 and 850 million km from the sun***

Orbits: ***Every 6.5 years***

Spins: ***Every 12.5 hours***

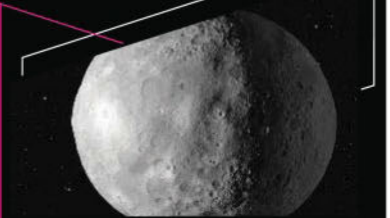
Appearance: ***Misshapen chunky duck***

Composition: ***Dirty ice ball, ice and dust tail***

Size: ***Roughly 5 km by 3 km***

First visited: ***ESA Rosetta mission, 2014***

CERES



Ceres

Discovered: ***1801***

Classification: ***Asteroid; dwarf planet (since 2006)***

Home: ***Asteroid belt between 380 and 450 million km from the sun***

Orbits: ***Every 4.6 years***

Spins: ***Every 9 hours***

Appearance: ***Round and pockmarked, distinctive bright spots***

Composition: ***Icy dirt ball, possible liquid water inside***

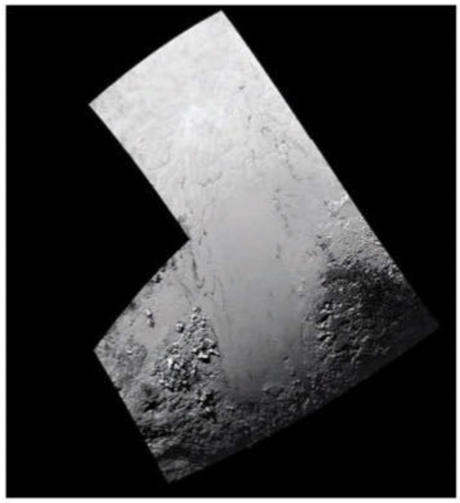
Size: ***950 km in diameter***

First visited: ***NASA Dawn mission, 2015***

CHRIS BUTLER/SCIENCE PHOTO LIBRARY

Pluto: the world that's everything at once

The first images from the dwarf planet's surface baffle and amaze, say Jacob Aron and Joshua Sokol



NASA/JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE

PLANET, dwarf planet or the little world that could? One thing's for sure: it's the Frankenstein's monster of the outer solar system, because Pluto looks like bits of different worlds stitched together.

Mountains like Earth's, 3 kilometres high and made of frozen water. A comet's tail of escaping gas pulled back by the solar wind. Smooth surfaces like the icy veneer of Neptune's moon Triton next to cracked terrain that resembles the highlands of Mars.

This variation stunned researchers when NASA's New Horizons spacecraft beamed back the first close-ups of Pluto and its moons in July. The dwarf planet is unlike any other world we've ever visited. So is its largest moon, Charon.

That surprise has turned even the most seasoned Pluto experts into wide-eyed surveyors, cataloguing the dwarf planet's many mismatched oddities and trying to find the joins. The maps from New Horizons, still being downloaded and analysed, are proving hard to interpret – and harder still to explain.

Smooth regions on the surface of both Pluto and Charon were the biggest shock in the first wave of data. Prior to the probe's arrival, researchers expected to see a pair of heavily cratered worlds, bombarded since their formation in the early days of the solar system. Counting craters provides a way to date a planet's surface because impacts build up at known rates over time. Now we see that while both Pluto and Charon have their share of asteroid scars, the existence of unmarked terrain means they must have been geologically active fairly recently, at least on planetary timescales.

"We now have an isolated small planet that is showing activity after four and a half billion years," said mission leader Alan Stern at the press conference where he revealed that the first high-resolution image of Pluto's surface seemed to have no craters at all. "I think that's going to send a lot of geophysicists back to the drawing board," he said.

Perhaps the most perplexing site of geologic activity is a region called Sputnik Planum, where surface ice is cut into polygonal chunks around 20 kilometres wide. "When I saw this image for the first time I decided I was going to call it 'not-easy-to-explain' terrain," says team geologist Jeff Moore of the NASA Ames Research Center in California. It might be that the surface is cracking like mud as it contracts, or that convection within Pluto is heating and melting the surface like a bubbling pot of porridge.

The hunt is on for the mechanism driving that activity, providing enough energy to smooth away craters after they form. These smooth surfaces are also seen on Neptune's moon Triton, another small icy body that was previously thought to resemble Pluto. But Neptune's gravity warms and remoulds Triton through a process called tidal heating.

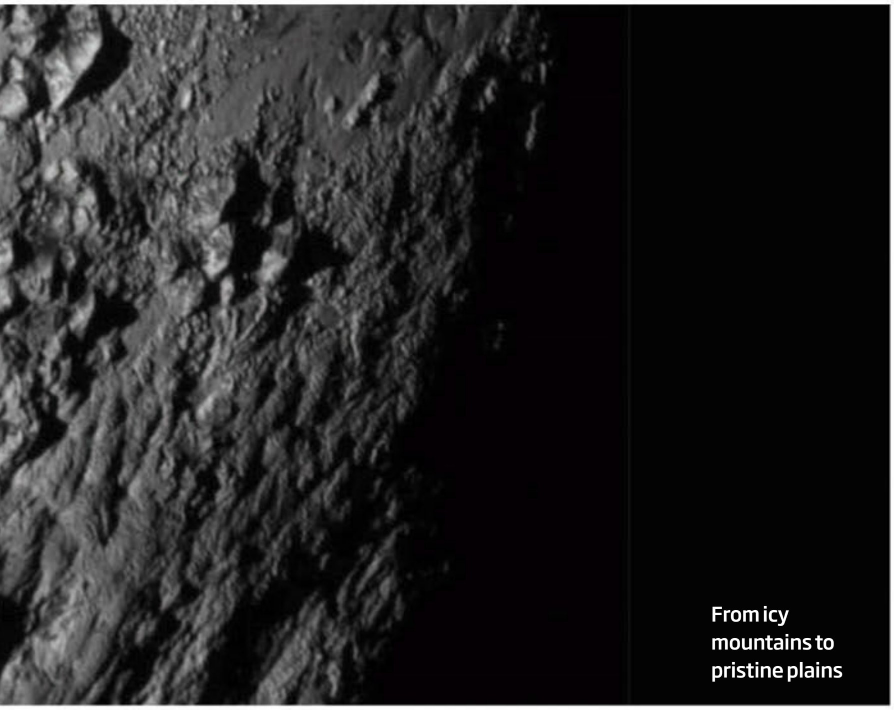
That same process can't still be active on Pluto and Charon, because they are tidally locked so always show the same face to each other. "We know that process is over now, but when was it over?" says Geoffrey Collins, a geologist at Wheaton College in Norton, Massachusetts. Pre-New Horizons, it was thought that a collision between 4.4 and 4.5 billion years ago between a proto-Pluto and a proto-Charon created the binary system we see today.

What if the smash-up was more recent, allowing the two worlds to retain energy later into the history of the solar system?

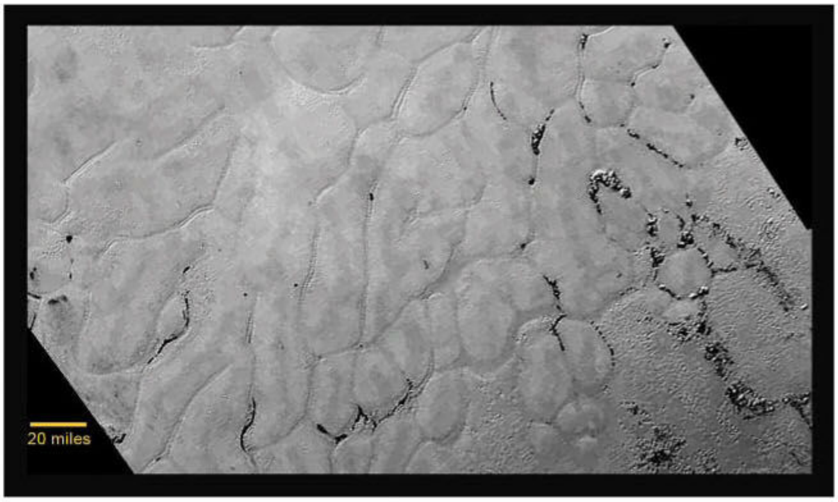
Pluto's insides could also be warmed by the slow breakdown of radioactive elements left over from the formation of our solar system, team geologists say. Alternatively, the gradual freezing of a buried ocean could be helping the dwarf planet hold on to the last glow of heat left over from its birth. More data is needed to draw any firm conclusions.

The jagged mountains dotted across the high-resolution image of Pluto's surface, thought to be made of frozen water, also hint at unexplained activity below. "The traditional way of growing a mountain is you smoosh stuff together and it pops up, or you pull them apart and you get a volcano. These things didn't look like any of that," said team member Will Grundy of the Lowell Observatory in Flagstaff, Arizona.

Collins thinks these mountains could



From icy mountains to pristine plains



"The team is cataloguing the dwarf planet's many mismatched oddities and trying to find the joins"

rule out some kinds of activity. To him, they resemble nunataks, which on Earth are the tips of rocky mountains sticking out of glaciers. Nunataks on Pluto could be water ice sticking out of other ices, possibly frozen methane, which have snowed down from Pluto's atmosphere and smothered the craters. It's hard to tell because we don't know enough about how different ices interact at very low temperatures.

It isn't just Pluto's geology that hints at surprising vitality. When New Horizons was five days out from Pluto, it saw ionised nitrogen escaping from the atmosphere, a far stronger signal than the team expected. The first set of results showed that the gas was forming a tail behind the Pluto system, blowing in the charged particles of the solar wind. That confirmed a long-held suspicion that Pluto is undergoing a process also found in the distant past of other worlds, providing us with a window backwards in time.

We've never been able to study gas escaping on this scale before because the process is more or less complete on other planets. New Horizons saw it happening in real time, both spying the glow of ionised nitrogen and catching the particles directly with on-board sensors.

Earth's first atmosphere, a poisonous brew of hydrogen and helium, is thought to have escaped in much the same way.These lighter gas molecules were the only ones able to break away from our planet's stronger gravity. On Pluto, nitrogen, which is heavier and makes up most of both Earth and Pluto's present-day atmosphere, can also escape.

The same thing probably also happened on early Mars, wicking water vapour out of the atmosphere and drying out the planet. "Exploring Pluto is testing our ideas about this very escape on Mars," says team member Fran Bagenal of the University of Colorado in Boulder.

So far, it looks as if about 500 tonnes of nitrogen gas leave Pluto's atmosphere every hour, Bagenal says. Nailing down the exact rate of escape is a priority for the mission – it will help the team make comparisons with theories of similar behaviour in the solar system's ancient past. And since New Horizons discovered that the atmosphere is thinner than expected, that gas is probably being formed as a result of evaporation at the dwarf planet's surface.

That could mean plumes of nitrogen are erupting from the surface just as the Voyager probe saw on Triton, team geologists say. Smudges deposited near dark shapes could be indirect evidence of plumes, although the team thinks these features look more like streaks where winds as fast as a few metres per second have blown material around surface obstacles.

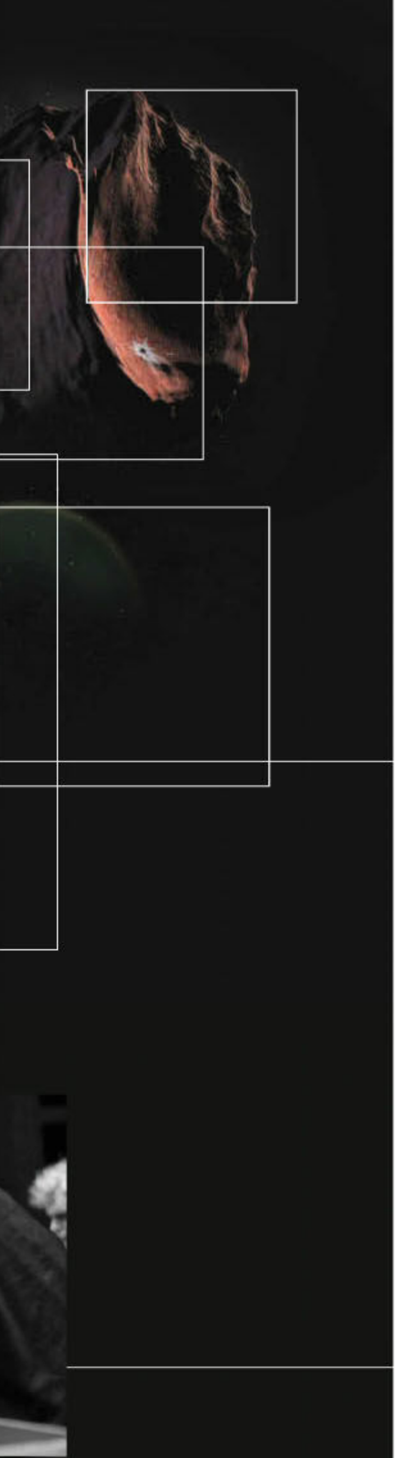
The team hoped these plumes would be revealed by New Horizons as it sped away from a rapidly shrinking Pluto, lit up in the distant sunlight. But no such luck. A more plausible explanation is that a thick layer of nitrogen ice over Pluto's surface is turning to gas and floating up into the atmosphere.

And there's so much more to learn from the Pluto system. Its largest moon, Charon, is far more varied than the team expected, and hosts a mountain within a moat that has researchers baffled. Hydra, one of the four smaller moons, is lumpy like a peanut and probably covered in dirty water ice. We've also had a brief look at another, Nix, as well as glimpses of Kerberos and Styyx, the final two (see "Beyond Pluto", page 52).

Researchers are as fascinated as they are confused by what they're seeing, and the findings at Pluto show it is every bit as complex as the other planets we've explored. "I think the solar system saved the best for last," said Stern. ■

Beyond Pluto

Gliding ever deeper into the wilderness, the New Horizons probe is set for one final hurrah before it falls silent forever. **Will Gater** reports



TOP: NASA/JOHNS HOPKINS UNIVERSITY APL/SWRI/STEVE GRIBBEN; DROP INS: MICHAEL SOLURI; FAR LEFT: NASA/JOHNS HOPKINS UNIVERSITY APL/SWRI

WITH Pluto rapidly shrinking from view, NASA's New Horizons probe is slipping further into a vast unexplored wilderness known as the Kuiper belt. This great frigid expanse beyond the gas giant Neptune is home to millions of icy bodies, known as Kuiper belt objects, many of which are thought to be pristine remnants from the birth of our planetary neighbourhood some 4.6 billion years ago.

As the world continues to gawp at breathtaking images of the Kuiper belt's most famous inhabitant, Pluto, the plucky little probe that snapped them is about to embark on one last fly-by. It won't be easy: New Horizons's latest target is much smaller than the dwarf planet and there is uncertainty about its exact position. But if all goes to plan, this valedictory mission could yet be the most revealing phase of an awe-inspring journey.

"The Kuiper belt is a truly key population for understanding how the solar system evolved after the planets formed," says Michele Bannister of the University of Victoria in Canada, who works on the Outer Solar System Origins Survey – a project to map the Kuiper belt from Earth to get a handle on how it formed. By capturing the first close-up views of one of its smaller inhabitants, New Horizons's final act before it falls silent could help rewrite the history of our cosmic neck of the woods.

This last assignment is far from an afterthought. In fact, the visit to a second Kuiper belt object was something the New Horizons team thought about from the outset, says John Spencer of the Southwest Research Institute in Boulder, Colorado, who is part of the planning team for the extended mission. "Back when the spacecraft was still being designed in 2002, we were thinking pretty seriously about what we would need to do."

NASA mission control has already steered New Horizons toward its final destination

Most importantly, the probe's designers made sure it would have sufficient fuel reserves to fire up the thrusters that would steer it towards another Kuiper belt object. "If we couldn't change course we would have no ability to get close to anything other than by the incredibly unlikely chance that we would just happen to breeze right by something," says Spencer.

The big question, though, was exactly what to aim for. Although estimates suggest there are hundreds of thousands of icy bodies in the Kuiper belt (see "Welcome to the boonies," page 54), the challenge was to discover objects within reach of New Horizons.

With Spencer at the helm, the search team started scanning the far reaches of the solar system in 2004, using the Subaru telescope in Hawaii. They wanted to check there was nothing large and interesting enough to warrant a tweak to the Pluto fly-by schedule. There was not. So two years later, when New Horizons was launched on its epic voyage, it carried enough fuel to explore a small portion of the Kuiper belt, but its post-Pluto destination was still unknown.

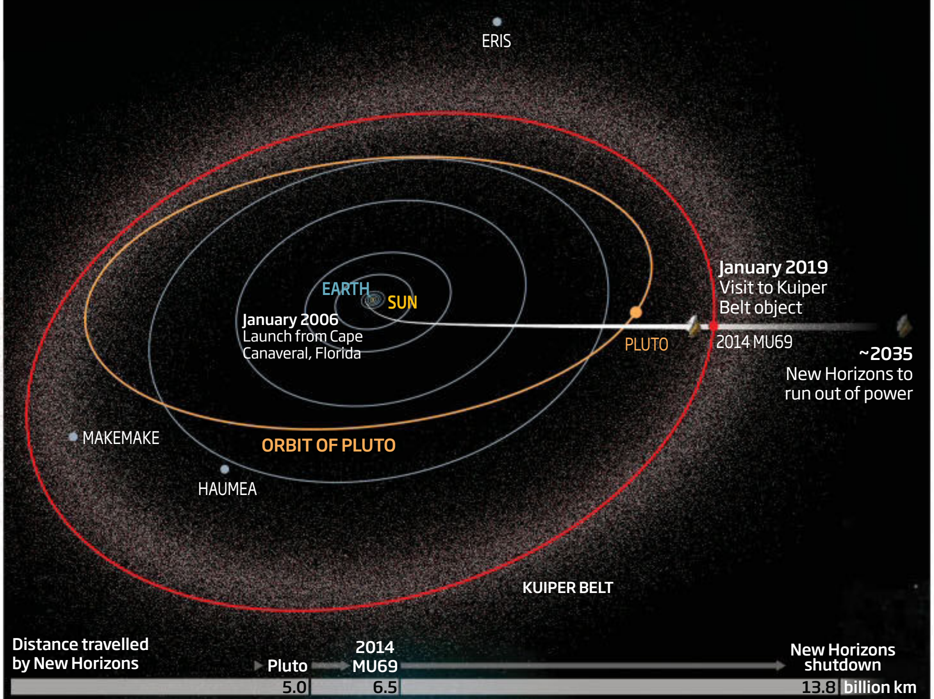
By 2011, with New Horizons set on a specific path, the team had a much narrower section of sky to scour, in the constellation Sagittarius. But now there was a fresh obstacle: it would be difficult to pick out faint objects against the myriad Milky Way stars in the background. "We were quite concerned by late 2013,"says Spencer. "We'd had three years of searching and we were finding it very challenging to look in the very dense star fields."

Eventually the group managed to discover some 50 Kuiper belt objects lurking in front of this sparkling backdrop. Unfortunately, all of them lay beyond the range of the outbound New Horizons. "I think the closest one that we found would have required about 50 per cent more fuel than we actually had in the tank," says Spencer. "We knew we were getting down to the ballpark of where we needed to be, but we certainly hadn't got what we needed at that point. That was why we turned to Hubble."

The Hubble Space Telescope promised more detailed images. But first the team had to prove to Hubble bosses that they stood a good chance of discovering potential targets, and then they had to sift through an avalanche of data. "It was nerve-racking," says Spencer, ›

Final fly-by

Before it falls silent forever, the New Horizons probe is heading deep into the Kuiper belt for one last mission: a close encounter with a pristine remnant from the early days of the solar system - 2014 MU69



WELCOME TO THE BOONIES

We suspected there were frozen badlands beyond the planets long before we saw them. In 1951, astronomer Gerard Kuiper made a strong case for the existence of a vast swathe of icy bodies beyond Neptune's orbit. It wasn't until 1992, however, that astronomers spotted something other than Pluto out there. It was the first real evidence of an immense ring of debris at the outermost edges of the solar system - a region now known as the Kuiper belt.

Astronomers have since discovered roughly 1500 Kuiper belt objects orbiting between 4.5 and 7.5 billion kilometres from the sun. And yet we've barely scratched the surface. We know that most of them are tens of kilometres across but there are a few larger bodies out there, including Pluto and its largest moon Charon. The dwarf planet Eris, for instance, appears to be almost the same size as Pluto, and might have similar geological activity. The region is also thought to be the source of most short-period comets, which take less than 200 years to orbit the sun.

But our best estimates suggest this planetary wasteland should contain hundreds of thousands of icy bodies - remnants from the solar system's early days - and we know almost nothing about all but a handful of them. "We are still pretty ignorant about many aspects of the Kuiper belt," says Wes Fraser of Queen's University Belfast, UK. "For one thing, we don't know much about what they are made of. They must have some sort of rock inside, but what is it?"

The Kuiper belt holds secrets about how the planets formed and how our planetary neighbourhood evolved. It might even provide insights into why Pluto didn't make it to planet status, says Fraser.

Trouble is, the region is so distant that even with space telescopes it has been difficult to get to know its inhabitants. No wonder planetary scientists are so excited by the prospect of a close encounter with one of them (see main story).

JOHNS HOPKINS UNIVERSITY APPLIED PHYSICS LABORATORY/SOUTHWEST RESEARCH INSTITUTE (JHUAPL/SWRI)

The New Horizons probe is about the size of a baby grand piano

SCOTT ANDREWS/GETTY

"but mostly it was just kind of exhilarating."

In 2014, the team finally struck gold: two Kuiper belt objects, 2014 PN70 and 2014 MU69, both of which would be within New Horizons's reach. The amount of fuel required to steer a course towards the former would have left precious little for precision manoeuvres around the object, compromising the mission's scientific objectives, says Spencer. "So it was a fairly straightforward choice in the end." New Horizons would go to 2014 MU69.

The team is hoping that NASA will officially sign off on the extended mission to 2014 MU69, a decision that won't be made until later this year. But Spencer and his colleagues have already commanded the four engine burns needed to send the probe in the direction of its post-Pluto target, currently roughly 1.5 billion kilometres from the dwarf planet (see diagram, page 56).

Assuming the extended mission gets the nod, when the spacecraft visits 2014 MU69 in January 2019, we can expect to see an object very different from Pluto. Measurements of its brightness suggest it is between 30 and 40 kilometres across – far smaller than the 2370-kilometre-wide dwarf planet. It is also expected to be irregularly shaped and covered with craters, says Spencer. And as a member of the "cold classicals" group, which move in relatively circular orbits compared with other Kuiper belt objects, it should be reddish in hue.

Just as with Pluto, New Horizons's encounter with 2014 MU69 will be fleeting, and its instruments will have to work flat out

to gather data on their icy quarry. "We'll be using our infrared spectrometer to map the composition of the surface and the ultraviolet spectrometer to look for any signs of an atmosphere," says Spencer. "We don't expect to see an atmosphere on something this small but we sure will be ready for surprises."

Atmosphere or not, getting up close and personal with 2014 MU69 should help to reveal whether Pluto was formed from such objects and could help to address fundamental questions about how planets form.

According to our best theory, planets are born out of protoplanetary discs – great whirls of dust and gas spinning around the midriff of a young star. The material comes together to form small clumps, which pull in more material thanks to their modest gravity. Soon you have the beginnings of planets, known as planetesimals, and eventually planets.

Objects like 2014 MU69, as residents of a region that has remained largely undisturbed since the early days of the solar system, are thought to be the ancient leftovers from this planet-forming process. "We would very much like to know what processes formed the primordial planetesimals – the original building blocks of the planets – and 2014 MU69 is the closest we have yet come to flying by one of these," says planetary astronomer Alex Parker, also at the Southwest Research Institute, who helped discover 2014 MU69.

Its relatively undisturbed location far from the sun – what Parker calls its "deep-freeze orbit" – has helped to preserve it as a time capsule. So this mystery chunk should tell us about the processes by which it was formed as well as shed light on how its ilk helped to build the planets.

Scars of violence?

If New Horizons observes fresh impact craters, for example, it may reveal something about the formation of bodies like Pluto. Any newish pockmarks will have uncovered material from below the surface of 2014 MU69 – stuff that hasn't been altered by cosmic rays, say, or ultraviolet radiation. That should allow us to figure out its composition, says Spencer. "We can compare that to what we expect objects like Pluto to have been made of."

Such observations could also help to solve another great mystery: how the solar system came to be arranged in its particular way. Current models suggest that the gas giants were once bunched up much more tightly than they are today, encircled by a substantial disc of planetesimals. Then something destabilised this cosy arrangement, hurling the planets into their present-day positions. The outer disc was shaken up too, although some of it endured to form the Kuiper belt.

Scientists have run many simulations of this period, and yet precisely how this process played out remains a conundrum. Was it a violent upheaval or a more gentle migration? To answer that, we need to know exactly how massive the disc of planetesimals was before the gas giants migrated. And here is where 2014 MU69's craters could help.

"In a way the craters actually preserve a reflection of the amount of mass that was around these objects at some point," says Wes Fraser of Queen's University Belfast, UK. The idea is that if an object is riddled with scars, that would suggest there were once lots of objects around to crash into it, whereas if an object has only a few craters, it was probably surrounded by fewer objects. By studying the sizes and numbers of craters in New Horizons's images, scientists should get a better idea of the mass of the disc. And by feeding that back into current models, they should get a clearer picture of how the solar system evolved into what we see today.

For Bannister and her colleagues at the Outer Solar System Origins Survey, the fly-by could also provide context for their studies of the orbits and surface compositions of distant Kuiper belt objects. "We can finally match together what we see from Earth only as a tiny point of light with the actual ices and hydrocarbons that cover its surface," she says. And although 2014 MU69 will undoubtedly be the centre of attention during this post-Pluto mission, the team behind New Horizons will also study other objects the probe glimpses.

As for the little probe itself, once it has completed its work in the Kuiper belt, it will glide ever further into the outer reaches of the solar system. It will continue to send back data, including measurements of the solar wind – the stream of charged particles flowing from our star – until its radioactive power source runs out, probably some time in the mid-2030s.

Regardless of when we lose touch, the fate of New Horizons is set. With the Kuiper belt frontier traversed, it will drift off into the depths of the Milky Way – its precious data stored on Earth and its journey into darkness complete. ■

WHERE SPACECRAFT GO TO DIE

Once New Horizons has slipped past its latest target in the Kuiper belt, its course will whisk it deep into the Milky Way. It will follow an armada of space probes that have sailed into quiet retirement or crashed into violent oblivion.

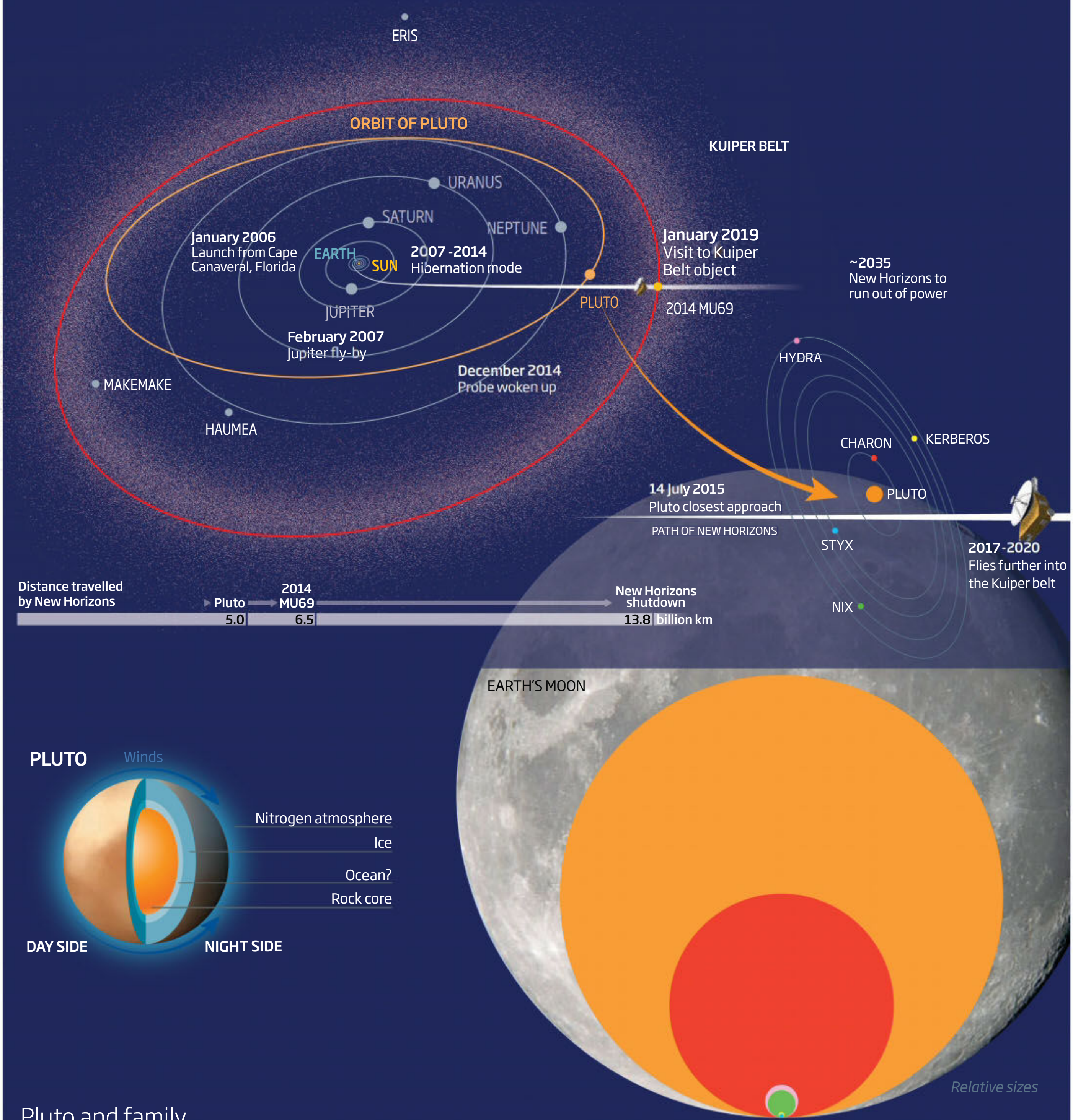
Like New Horizons, the two Voyager spacecraft - which toured the outer planets in the 1970s and 1980s - are heading for interstellar space. And data returned by Voyager 1 has led some to argue it has already left our solar system (see "Are we nearly there yet", page 57).

Others have gone out with a bang. The Galileo probe to Jupiter was commanded to plummet into the gas giant so as not to litter the planet's moons with earthly debris. And the Rosetta mission, currently hovering around the comet 67P Churyumov-Gerasimenko, will be deliberately crashed into its icy quarry this year. A similar fate awaits Cassini, due to plunge into Saturn in 2017.

A few spacecraft are lucky enough to retire on the planet they went to see. When the adventures of the Mars rovers Opportunity and Curiosity eventually come to an end, for instance, they will sit motionless on the Red Planet's surface, slowly gathering ochre dust as the Martian breeze swirls around them.

Final fly-by

Before it falls silent forever, the New Horizons probe is heading deep into the Kuiper belt for one last mission: a close encounter with a pristine remnant from the early days of the solar system – 2014 MU69



Pluto and family

	PLUTO	CHARON	HYDRA	NIX	KERBEROS	STYX
Discovered	1930	1978	2005	2005	2011	2012
Diameter	2370 km	1207 km	57-177 km	42-148 km	13-34 km	10-25 km
Surface gravity	6.7% of Earth's	2.8% of Earth's	–	–	–	–
Composition	70% rock, 30% ice	55% rock, 45% ice	–	–	–	–
Orbital period	–	6.3 days	38 days	25 days	32 days	20 days
Mean distance from system centre	–	19,600 km	65,000 km	49,000 km	58,000 km	43,000 km

Are we nearly there yet?

The journey out of our solar system was never going to be straightforward. **Nigel Henbest** jumps aboard

HEARD the joke about déjà vu? Several times. Then you've probably heard the news about NASA's Voyager 1 spacecraft leaving the solar system. Its departure has hit the headlines many, many times – only for NASA to change its mind. Over the past decade, the veteran space probe has been in, out and even shaken all about.

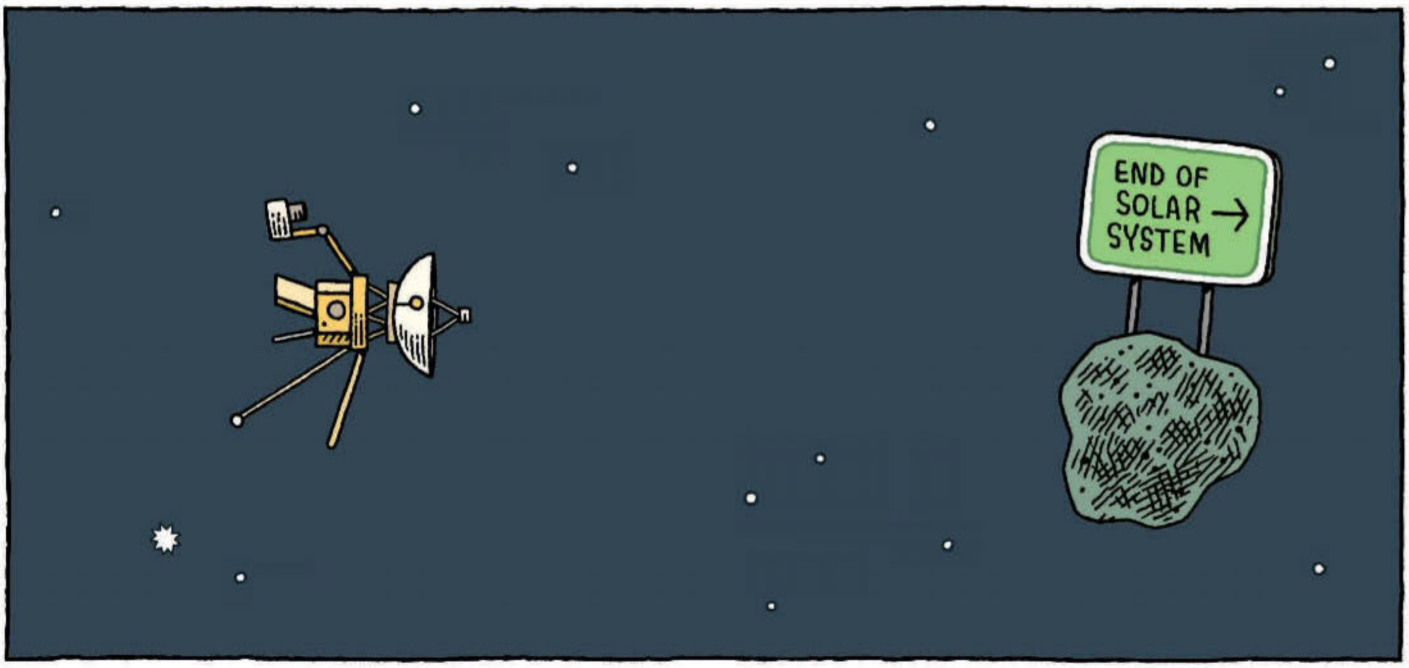
In September 2013, though, it looked like this game of space hokey-cokey was finally over. Voyager 1's normally cautious project scientist Ed Stone declared that, after 35 years, the probe had left for real. "This is humankind's historic leap into interstellar space."

So why has it been so hard to tell if Voyager 1 has crossed the border from the solar system to interstellar space? And can we be sure that it has really made it this time? If the latest results are anything to go by, the story of Voyager 1 is far from over.

Mission control isn't what you might imagine. Forget the cavernous darkened room with rows of anxious engineers and scientists intently watching giant screens on the walls. What I'm ushered into is a single-storey building next to a busy traffic junction just north of Pasadena in California. Inside, there's a small open-plan office. It is empty apart from two pairs of computer screens aglow with tables of figures, one set green, the other blue. From the ceiling hangs a sign: "Mission Controller".

It hasn't always been so low-key. When NASA launched its twin Voyager 1 and 2 spacecraft in 1977, mission control was located at the Jet Propulsion Laboratory in Pasadena. But times change: "We've been here since 2003, when NASA needed the control room for the Spirit and Opportunity rovers on Mars," says Suzy Dodd, the Voyagers' project manager.

What haven't changed are the giant radio ears around the globe picking up faint whispers from the distant probes. They beam data to the control room for sending on to the science teams. The two blue screens display messages from Voyager 1; the green



TOM GAULD


NASA

Way to go: Voyager 1 blasted off in September 1977

screens are full of posts from Voyager 2.

For all the similarity in the displays, there's one huge difference. Voyager 2 is telling us about conditions in the heliosphere – the giant magnetic bubble surrounding the sun where we and all the planets reside. But Voyager 1 is flying higher, through a region of the universe where no probe has ever been before: the space between the stars.

Or is it? The hinterland of the solar system is a confusing place. For a start, where does it end? Voyager 1 has passed all the planets – it crossed Neptune's orbit back in 1988 – and is now over 130 times further out from the sun than Earth. Yet it's still well within the sun's gravitational embrace, and won't break free for thousands of years when it passes the remote Oort cloud, homeland of the comets.

To settle the matter, the Voyager 1 team need to find out whether the probe has burst through the heliosphere. This is formed from the hot wind of particles, laced with magnetic fields, pumped out by our star. The solar wind sweeps past Earth and travels beyond Neptune until it eventually loses its oomph when it hits interstellar space – marking the edge of our solar system.

Although nothing has visited interstellar space before now, Priscilla Frisch at the University of Chicago has been able to characterise it by looking at its imprint on light from nearby stars. Far from being a featureless void, interstellar space contains clouds of gas and dust that are being blown about by the force of ancient supernova explosions. Frisch has shown that our solar system lies inside a cloud about 40 light years across, called the Local Interstellar Cloud.

Here a teaspoon of space contains about half a dozen atoms, which is far denser than the solar wind when it reaches the edge of the solar system.

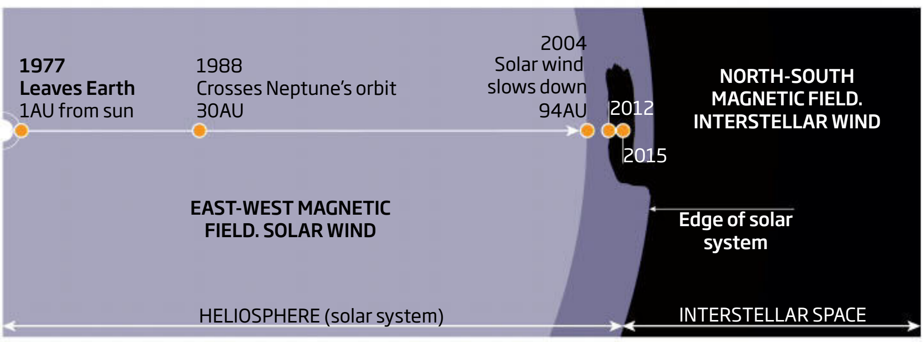
This difference helps us tell if Voyager 1 has left the heliosphere and crossed into interstellar space. Amazingly, most of its scientific instruments are still working, though to save power NASA controllers long ago switched off the cameras that took close-up images of Jupiter and Saturn.

In August 2012, Voyager 1's instruments measured a dramatic drop in the number of solar-wind particles. At the same time, they detected a much higher rate of arrival of cosmic rays – high-energy particles from interstellar space that struggle to penetrate the heliosphere's magnetic shield. Things seemed pretty clear-cut: Voyager 1 had left the solar system.

However, a third indication refused to fall into place. Voyager 1's on-board compass should have picked up an abrupt change in the magnetic field at the edge of the heliosphere. "Yet the field direction was just really incredibly flat," says Alan Cummings, who was the last

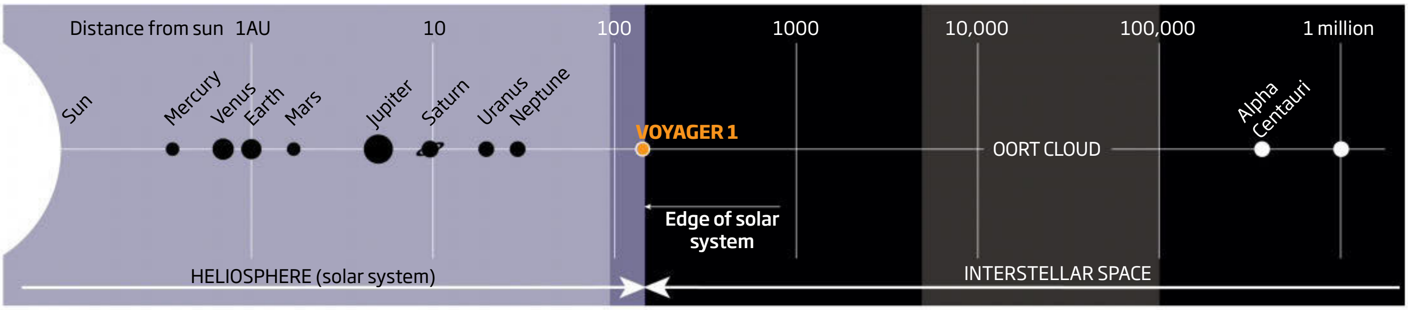
Heading for the edge

The edge of the solar system is a confusing place. In 2012, Voyager 1 seemed to have crossed into interstellar space but its magnetic field reading still matched that of the solar system. Some researchers believed the spacecraft was sitting in a finger of interstellar gas that breached the solar system



Voyager 1's place in space

NASA's Voyager 1 spacecraft is 133 times farther from the sun than Earth, but we still don't know if it has left the solar system



person to see Voyager 1 before lift-off.

Faced with this contradiction NASA scientists were sitting on the fence. Then came what seemed to be the clincher, from an unexpected direction. In April 2013, Voyager 1 felt the gas around it shaking violently, as a giant eruption from the sun 400 days earlier finally reached the spacecraft. The strength of this pounding showed that Voyager 1 was in a region far denser than the interior of the heliosphere. After pondering the finding for a few months, Stone – as NASA's spokesman – made the historic declaration: "Voyager 1 is now bathed in matter from other stars."

Ribbon in the sky

So far, the interstellar medium is what we'd bargained for, says Stone. It is 40 times denser than the gases in the heliosphere, just as we would expect for a wall of gas piling up at a largely impenetrable boundary. Yet for all the hype surrounding Voyager 1, the doughty old spacecraft isn't the only show in town. The remarkable Interstellar Boundary Explorer (IBEX) satellite is mapping the edge of the solar system too – without leaving Earth's orbit.

IBEX is on the lookout for high-speed atoms travelling towards Earth from beyond the planets. These atoms started out as electrically charged ions ejected from the sun. When they reached the edge of the heliosphere, its magnetic field whirled them round in all directions. Some of the ions picked up electrons from the interstellar gas and became neutral atoms. At that instant, they stopped feeling the magnetic force and shot off in all directions, like a whirling conker flying away when the string breaks (or think of the hammer throw). Some of these energetic atoms head back home and are scooped up by IBEX, allowing the satellite to map where the gas is found and hence the edge of the solar system.

"The Voyager and IBEX observations are complementary," says Dave McComas of the South West Research Institute in San Antonio, Texas, and head of the IBEX team. "A good analogy is from medicine, where the global imaging (IBEX) is done by a CT scan, while a few precise local measurements (Voyager) of a tumour require sampling by a biopsy."

One surprising feature stands out. IBEX's map shows a prominent band across the sky, indicating a region at the solar system's edge sending far more atoms back towards Earth. "The IBEX ribbon was a shocking and fascinating discovery," says McComas.

It's most likely that the ribbon is caused by the magnetic field found outside the solar system, and so the orientation of the IBEX ribbon reveals the direction of the magnetic field in interstellar space. According to these results, it aligns roughly north-south. If we could see it in the sky, one magnetic pole would lie in the northern sky near the bright star Arcturus, and the other in the south in the dim constellation Eridanus.

Further confirmation comes from Frisch. Her team has been plotting the direction of the magnetic field in the Local Interstellar Cloud by observing the light from nearby stars. The cloud's magnetism regiments its microscopic grains of dust, so they act like the filters in a pair of Polaroid sunglasses. "We're finding the interstellar magnetic field has a direction that nearly agrees with the magnetic field direction from the IBEX ribbon," she says.

But what of that pesky reading from Voyager 1? The compass needle on board is still resolutely pointing east-west – the direction of the magnetic field within the heliosphere. What gives? When the findings first came back, Nathan Schwadron of the University of New Hampshire in Durham proposed a contentious new idea: Voyager 1 might not have left the solar system after all.

That clearly chimed with the magnetism readings. But Voyager 1 had indisputably crossed into a region of dense interstellar matter. So Schwadron suggested that Voyager 1 was flying through a finger of interstellar gas that had penetrated into the heliosphere.

Working with McComas, Schwadron pointed to an analogy with Earth. "Portals" sporadically open in Earth's magnetic bubble, letting in particles from the solar wind that cause spectacular auroras. Scale this up to the sun's magnetic bubble, and similar portals could allow interstellar material to enter the heliosphere without changing the magnetic field direction (see diagram, left).

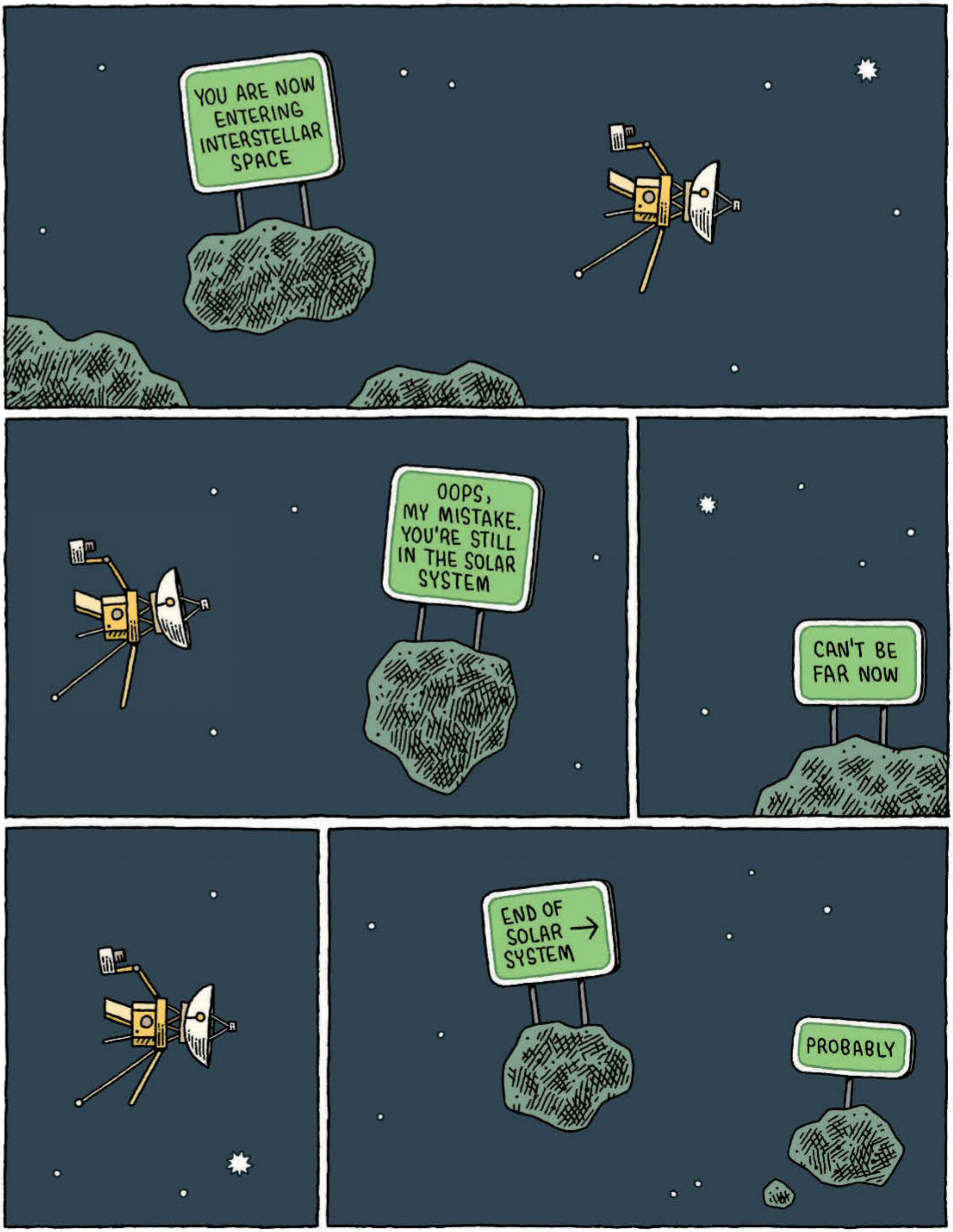
That was in 2013. But Schwadron's more recent work proposes another explanation for the mismatch. As the interstellar magnetic field drapes itself across the heliosphere's curved outer edge, certain regions may experience a distorted sense of magnetic north. If this is indeed the case, says Schwadron, Voyager 1 would now be past the heliosphere, travelling through the magnetically muddied region immediately beyond it. But true interstellar space could still

> **"The announcement of Voyager 1's departure may have been premature"**

be a long way off. "It will certainly be exciting if future boundaries are observed," says Stone.

That means it's critical to keep in touch with Voyager 1 for as long as possible. The craft is slowly dying, as the power from its radioactive generators fades away. At mission control, I'm amazed that the feeble transmitters on board are still communicating with Earth – though at a measly 160 bits per second.

The science instruments on board don't eat up the electricity. "The main drain on power is the heaters which keep the electronics at 18 ›


YOU ARE NOW ENTERING INTERSTELLAR SPACE
OOPS, MY MISTAKE. YOU'RE STILL IN THE SOLAR SYSTEM
CAN'T BE FAR NOW
END OF SOLAR SYSTEM →
PROBABLY

TOM GAULD

to 20 °C," says Steve Howard of the Voyager team. Out in the cosmic deep freeze, that means a lot of power. NASA expects to keep all the instruments running until 2020. "We haven't talked a lot about what we do then," admits Cummings, "whether to switch them off in sequence, or share power." One option, says Howard, is to run the experiments without the heaters, to see if any of them work in the chill of space.

While Voyager 1 has been grabbing all the headlines, its sister craft may provide some of the answers to "Voyager's little puzzles", as Cummings puts it. Voyager 2 is heading out in a different direction and is still "only" 109 AU from the sun. I ask Stone when it's likely to reach the same intriguing region of space as Voyager 1. He laughs: "Nature will tell us!"

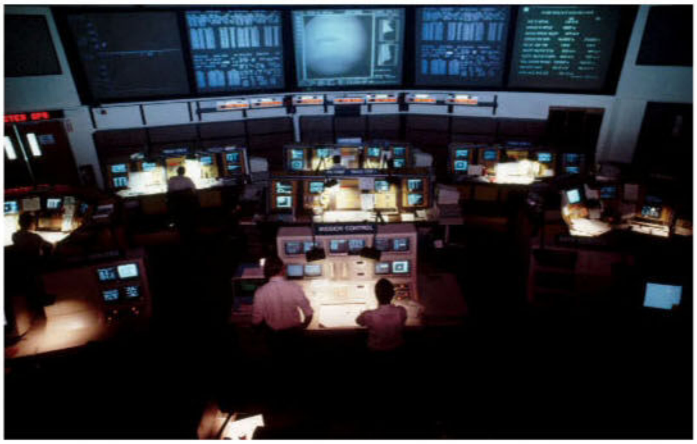
Send in the back-up

Voyager 2 passed a boundary within the heliosphere known as the termination shock, where the solar wind speed drops significantly, three years after Voyager 1 did. So Stone thinks it may encounter interstellar matter three years later, too. But the prediction is complicated by the gusts of wind rushing out from the sun. As Cummings puts it, "the whole heliosphere is breathing in and out".

More clues might come from a third NASA probe that is reaching for the stars. New Horizons sailed past Pluto last summer, and should break out of the heliosphere about 30 years from now (see "Beyond Pluto", page 52). "New Horizons is heading nearly directly between the Voyagers, and into the middle of the IBEX ribbon," says McComas, "so it would be very exciting data." At the moment, though, it looks like we will lose touch with the craft in the late 2030s, when it's not quite 100 AU from the sun.

The only certain way to get to the bottom of the Voyager 1 mystery is with new technology. Stone is looking forward to a purpose-built interstellar mission, with a modern set of instruments tuned to investigate the space it's swimming through. "The key thing is to get there much faster – as much as four times faster," says Stone. "With Voyager 1 it took us 35 years, and that's a very long time." The Interstellar Probe, now on the drawing board, would be shot into space by NASA's powerful new rocket, the inelegantly named Space Launch System. Accelerated through space either by an electrical propulsion system or a solar sail, it could reach a distance of 200 AU – almost twice as far as Voyager 1 lies now – in only 15 years.

Voyager mission control is more low-key these days (bottom) than it used to be (top)



BOTTOM NIGEL HENBEST; TOP ROGER RESSMEYER/CORBIS

McComas favours a different approach. He thinks a follow-up to IBEX would yield more science for the buck. A recent NASA report singled out another proposed craft, the Interstellar Mapping and Acceleration Probe – a larger and more precise version of IBEX. "IMAP is the most important next mission, and the global information it provides is far more important than another direct interstellar sample," says McComas.

"The Interstellar Probe could reach twice as far as Voyager 1 in half the time"

It's not just about the buzz of exploring a new realm: researchers are concerned about the effect that interstellar weather could have on Earth. "It's absolutely certain that the cloud around the heliosphere affects the environment where Earth lives," says Frisch.

Already, we are starting to draw up interstellar meteorological charts. By comparing the IBEX data with more primitive measurements from early probes and satellites, Frisch discovered that the gas beyond the solar system is changeable: the interstellar wind is gusty. "It's highly likely that the direction of the interstellar wind has changed over the past 40 years," she says. That's not surprising, she adds, as the solar system moves through the turbulent edge of the Local Interstellar Cloud.

As the wind sweeps past the solar system, it changes the way that the heliosphere deflects the energetic cosmic rays from deep space. The strength of the heliosphere's magnetic shield determines just how many cosmic rays get through and bombard Earth, triggering cloud formation in the atmosphere and so affecting our long-term climate. Cosmic rays also break up DNA in living cells, causing mutations that can lead to evolutionary changes.

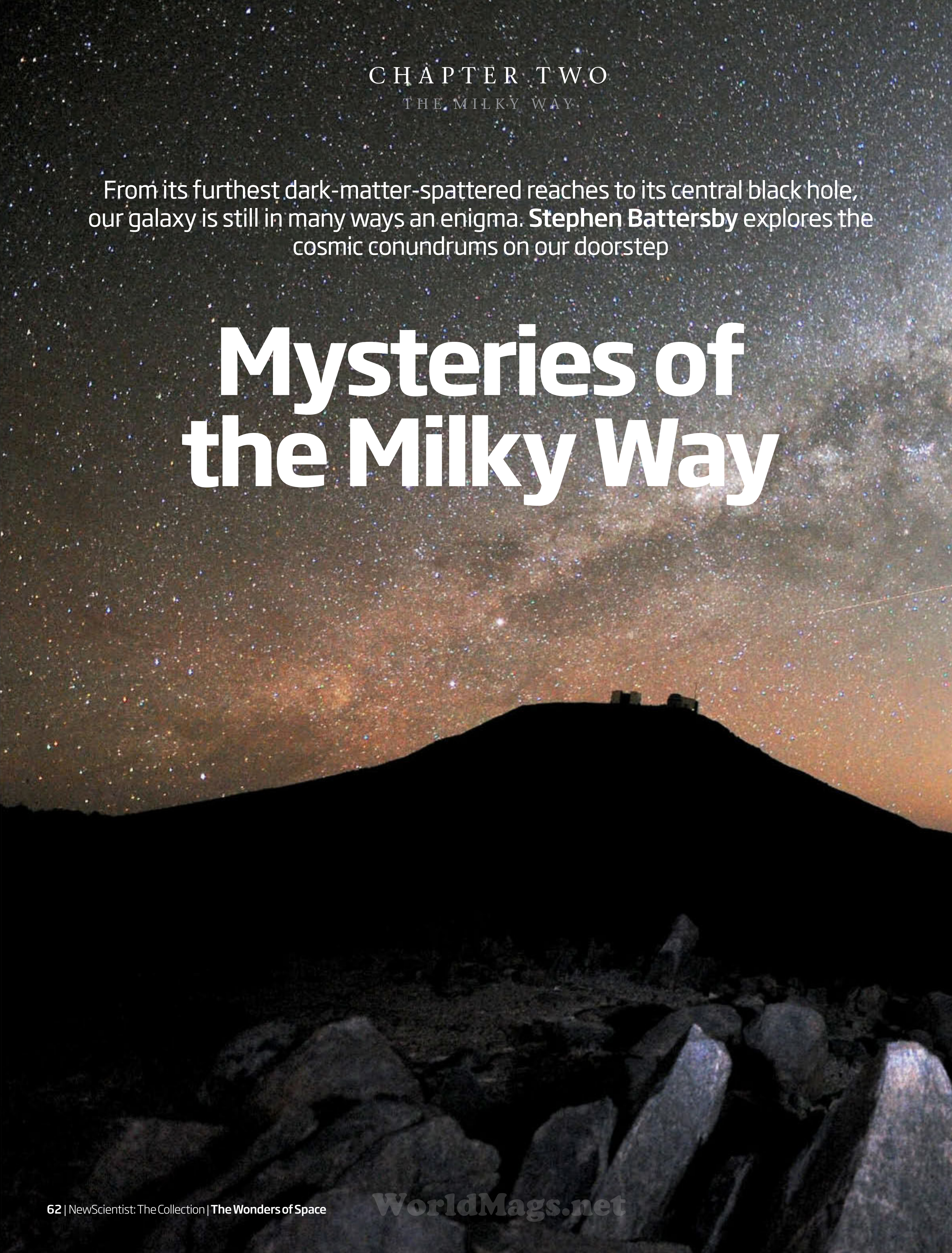
So as well as exploring deep space, Voyager 1 and its fellow explorers are also opening a window on the story of life on Earth, unravelling how the history of our planet has been moulded by the capricious storms of the galaxy. Expect plenty more news reports from the edge of the solar system. ■

CHAPTER TWO

THE MILKY WAY

From its furthest dark-matter-spattered reaches to its central black hole, our galaxy is still in many ways an enigma. **Stephen Battersby** explores the cosmic conundrums on our doorstep

Mysteries of the Milky Way



GERHARD HÜDEPOHL/ESO

Antimatter factory

Take 10 billion tonnes of antimatter and 10 billion tonnes of matter, and stir. Our galaxy mixes up one of these explosive cocktails every second, resulting in a warm inner glow of gamma radiation. Each photon created in this process carries an energy exactly equivalent to the annihilated mass of an electron and its antimatter counterpart, a positron. But what could be pumping out so many positrons?

Most galactic radiation – including visible light, ultraviolet, infrared, X-rays, radio waves and gamma rays of other energies – comes predominantly from the Milky Way's flat disc, where brilliant, short-lived new stars are formed. But the annihilation gamma rays come mainly from the galaxy's much smaller, bulging centre. "It is a unique case," says Nikos Prantzos of the Institute of Astrophysics in Paris, France.

There are some odd suggestions for this odd origin. The positrons could be created by decaying dark matter or blobs of exotic quantum matter called Q-balls; or they could be spat out by microscopic black holes or a tangle of cosmic strings, snags in the structure of space-time. Or it might be something more familiar. Supernova explosions in the Milky Way's disc create radioactive isotopes that emit positrons as they decay, and neutron stars and black holes can make antimatter when they feast on material from a sibling star. Some of these objects also inhabit the galactic bulge, although only enough to account for a fraction of the gamma-ray emission seen there.

The picture changes if the galaxy's magnetic field can funnel positrons from the disc into the central bulge. That depends on the field's basic shape, something we could learn from observations of how radio waves from distant sources are polarised. It also depends on whether positrons can travel tens of thousands of light years before being annihilated. That will be much harder to work out, because it depends on the small-scale details of magnetic fields and interstellar gas beyond the power of our telescopes.

If positrons can travel so far, another possibility opens up. "They could come from an event that happened long ago in the central black hole," says Prantzos. Starved of fuel, our galaxy's black hole is currently quiet (see "Mystery object: Sagittarius A*", page 66). Millions of years ago, though, it might have flared up, pumping out positrons that have since pushed out through the central bulge, creating a spherical halo of annihilation. Without a more detailed picture of the gamma-ray emissions, for now the truth remains out there.

Cosmic octopus

Step out into a clear night, far from the city lights, and you'll see a creamy streak of stars splashed across the sky: the "Milky Way" that has come to stand for our island universe. We see it as we stare through the flat, star-dense disc of our galaxy where we are also quartered. But what does our home look like from outside?

The short answer is we're not sure. Our telescopes unveil other galaxies in majestic detail, but introspection is much trickier. We think we live in a spiral galaxy of the sort we see scattered throughout the cosmos, but our lowly viewpoint in the galactic disc means we struggle to trace how its arms are furled, or even count how many there are.

Interstellar dust doesn't help: it blocks our view over distances of more than a few thousand light years, so we cannot map out distant spiral arms by their stars. We instead trace clouds of hydrogen atoms, which emit radio waves with a characteristic wavelength of about 21 centimetres. This long-wave radiation penetrates the dust, and by measuring the change in its wavelength - its Doppler shift - we can work out a cloud's speed towards or away from us. Comparing that with the ways in which different parts of the galaxy should rotate allows us to pinpoint a cloud's distance.

The resulting tentative maps suggest that the galaxy is a complicated, messy, many-armed spiral (see diagram, below).

But even that sketch is arguable. For a start, the galaxy's rotation is not precisely known, and individual clouds need not follow the average motion; different models produce different maps. And when we look towards or away from the galactic centre, where the clouds are moving almost sideways relative to us, the Doppler method is no help in determining their distance. "Arms can only be identified in segments," says galaxy mapper Robert Benjamin of the University of Wisconsin-Whitewater. "The task of piecing them together is left to the discretion of the astronomer."

A parallel mapping effort, which suffers from similar limitations, uses radio emission from carbon monoxide gas that hangs around parts of the galaxy. Since 2008, this method has revealed more details of the galaxy's structure, including what seem to be new arm segments. Better landmarks may be interstellar clouds where molecules of water or methanol act as lasers, amplifying a narrow line of microwave emission to produce bright pinpoints. These "masers" are so well localised that we can see how their position shifts as Earth orbits the sun, and thus triangulate their distance from us precisely. There are too few of them to map out the galaxy on their own, but they can be used to test the results of other methods. Maser range-finding could finally reveal the true face of the Milky Way.

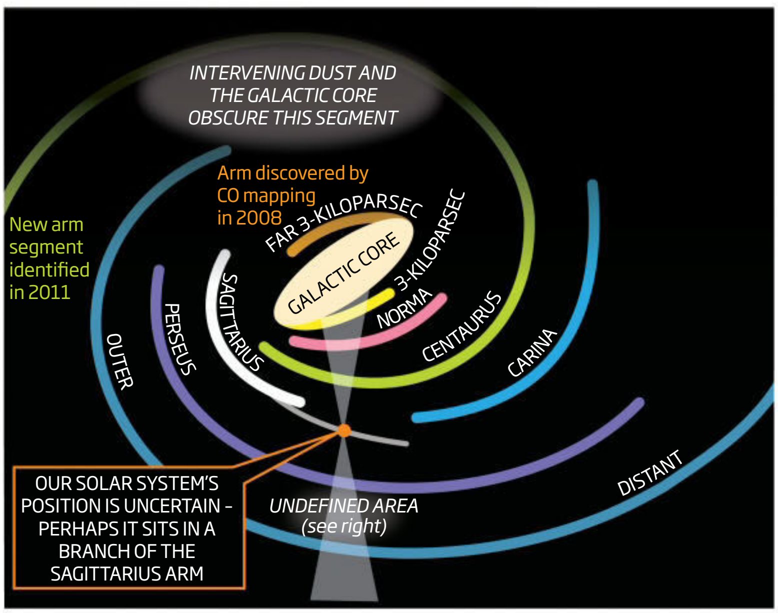
Mystery object: V838 MONOCEROTIS

In February 2002, this previously undistinguished star, about 20,000 light years away, briefly achieved a luminosity a million times that of our sun. The following month it happened again. And in April. It was first assumed to be a nova - a white dwarf that pulls gas off a companion until it triggers a thermonuclear explosion on its surface. But novas don't happen three times in quick succession and then go quiet.

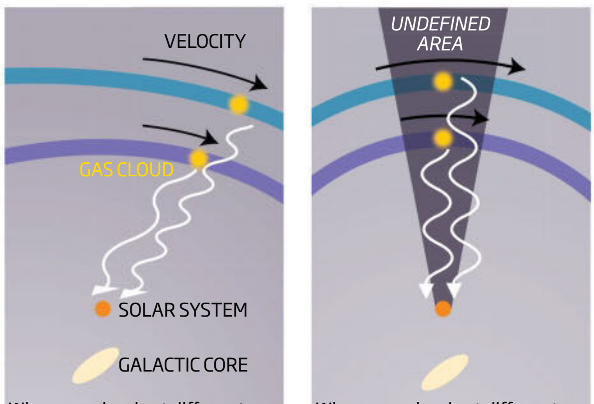
Was it a rarely seen flare-up near the end of a giant star's life? The screams of two stars colliding? Or did one star swallow three giant planets? What is certain is that the triple burst of light was reflected off nearby dust to surround the object with rapidly changing light shells, making it a true cosmic beauty.

In arms' way

Earth's location means that parts of our galaxy's spiral structure are hidden from us



The galaxy's rotational velocity increases with distance from its centre. That means we can use the Doppler change in radiation frequency to measure how far gas clouds are from us – in most cases



When gas clouds at different distances are moving at an angle to us, their apparent speeds towards or away from us create different Doppler shifts, telling them apart

Where gas clouds at different distances cross our field of view but are not moving towards or away from us, there are no Doppler shifts to tell them apart

NASA/ESA/THE HUBBLE HERITAGE TEAM (AURA/STSCI)

Sibling rivalry

The Milky Way and Andromeda are siblings: two great spirals that dominate our local group of galaxies. They have about the same total mass, and we used to think they were near-twins.

Not any more. "As we look in more detail, we see that they are quite different," says Alan McConnachie of the Herzberg Institute of Astrophysics in Victoria, Canada. Andromeda is the favourite child. It is brighter, with a wider disc of stars. The black hole at its heart is more than a hundred times as massive as ours. And while our galaxy is strewn with about 150 of the bright galactic baubles known as globular clusters, Andromeda boasts more than 400.

One might ask, a little plaintively, whether Andromeda is an exceptional specimen of galaxyhood. It seems not. In 2007, François Hammer and his colleagues at the Paris Observatory in France compared Andromeda and our galaxy with a sample of more distant galaxies. They found that whereas Andromeda is a pretty well-adjusted spiral, the Milky Way is an oddball – dimmer and quieter than all but a few per cent of its peers.

That is probably because typical spirals such as Andromeda are transformed by collisions with other galaxies over their lifetimes. These violent events shake up the galaxy's gas to form new stars and globular clusters, stir up the disc so it spreads farther out, and perhaps send some gas and stars plunging into the galactic heart to feed a more monstrous central black hole.

If this is to explain our sibling inequality, then the Milky Way must have lived relatively undisturbed. Except for encounters with a few little galaxies such as the Sagittarius dwarf, which the Milky Way is slowly devouring, we wouldn't have seen much action for 10 billion years.

Perhaps that is why we are here to note the difference. More disturbed spirals would have suffered more supernova explosions (see "(Kaboom!)", page 66) and other upheavals, possibly making the Milky Way's rare serenity especially hospitable for complex life. "We are still a long way from being able to answer that," says McConnachie, "but it's not a crazy suggestion."

Disappearing dwarfs

Pacing out their slow circuits over a billion years or more, over 30 small galaxies are thought to orbit the Milky Way. That might seem an impressive band of followers. Astrophysicists, though, think we should have an army.

That expectation is based on the prevailing model of how dark matter helps to form galaxies. Dark matter's composition is unknown, but it is thought to outweigh ordinary matter by five to one. In simulations of the early universe, the gravitational pull of cold clumps of dark matter draws in ordinary gas to form the first galactic building blocks.

The theory works well on large scales, reproducing the spongy pattern of galaxies and voids seen across the cosmos. On smaller scales, however, the simulations show that around every large spiral galaxy, dark matter clumps should sculpt thousands of dwarf galaxies.

One possible explanation for the discrepancy is that dark matter is not cold and clumpy, but a hotter gas of lightweight particles that forms small blobs less easily. Or perhaps dark matter doesn't exist at all: if the strength of gravity were to change at long range, that would do much that dark matter does without requiring so many dwarfs.

Tinkering with gravity is controversial. A less radical idea is that all those small dark-matter blobs do exist, but we just can't see them. Because their gravitational grip is weak, the gas could have been pushed out before many stars could form; a few giant stars may have blasted it out with their fierce heat and explosive deaths, for example. This theory is hard to check in simulations, says astrophysicist James Binney of the University of Oxford, because it depends on details such as the local gas density. "That has very fine structure which is way beyond the resolution of any simulation."

If the idea is right, though, it has a startling implication. Thousands of dark galaxies are arrayed around the Milky Way: a legion not lost, but invisible.

Mystery object: BLUE STRAGGLERS

The Milky Way's dense globular clusters are spherical swarms of red, lightweight and ancient stars, most of them more than 10 billion years old. A few globular-cluster stars, however, shine in blue-white light – suggesting something anomalously hot, young and bright.

We now think these "blue stragglers" are just as old as their companions, but have somehow been rejuvenated. Some may have sucked gas from a neighbouring star, compressing their central nuclear engine to make them burn faster and hotter. Others may be the offspring of stellar mergers – two cool red stars fusing to make one hot blue one. ›

(Kaboom!)

We can see the fiery brilliance of supernovae from more than halfway across the universe, billions of light years away. So why are we missing them in our own backyard? Comparison with similar spiral galaxies suggests that the Milky Way should host about three stellar explosions per century, but in the past millennium and a bit we have seen only five or six.

All of these have been within about 15,000 light years of us, while the Milky Way's disc is 100,000 light years across. We are missing the more distant explosions for a simple reason: our lowly viewpoint means most of the galactic disc is hidden behind interstellar dust.

As the blast wave of a supernova ploughs out into space, it energises particles to emit radio waves, which are not absorbed by intervening dust. Radio astronomers are now finding evidence of many of these supernova remnants. In 2008, one near the centre of our galaxy, called G1.9+0.3, was calculated to be the youngest known. Its light probably reached Earth about 114 years ago – perhaps marking Queen Victoria's funeral, had it not been for the black veils of dust in between.

There is still a dearth of remnants from the past 2000 years, but these explosions occur in complex regions of star formation where ionised gas clouds are also emitting radio waves, confusing the picture. "I think they're out there," says David Green of the University of Cambridge, who discovered G1.9+0.3 in the 1970s. "We have just not found them yet."

Mystery object: SAGITTARIUS A*

Sagittarius A* is a source of radio waves at the Milky Way's centre, thought to hold a huge black hole four million times the sun's mass. In some galaxies, such a black hole would be a fearsome source of radiation, blazing in light and X-rays as it feasted on nearby gas.

Not so in our galaxy. That is partly because Sagittarius A* has a much scantier supply of gas, but even so it is faint, and seems unusually inefficient at converting gas into heat and light. Some clues as to why might come soon, as a nearby gas cloud plunges into our listless giant's maw (see "The giant awakes", page 78).

Mystery object: S2

S2 is a fast, intense, blue-white star that frankly has some explaining to do. It orbits within a whisker of the galaxy's central black hole, Sagittarius A* (see left), swinging by at a speed of up to 5000 kilometres per second, or nearly 2 per cent of the speed of light.

At this distance, the black hole's gravity should shred gas clouds before they can condense into new stars. And although a star might migrate inwards from more tranquil breeding grounds, S2 is a bright young thing no more than about 10 million years old, whose lifetime seems too brief for such a trek.

NASA/SCIENCE PHOTO LIBRARY

Mystery object: SDSS J102915+172927

Most stars today contain a moderate hoard of heavy elements inherited from earlier stellar generations. Not so this one, more than 4000 light years away. Discovered last year, it is an almost pristine blend of hydrogen and helium, with just 0.00007 per cent of other stuff.

That is similar to the primordial matter emerging from the big bang. Such pure gas, lacking the carbon and oxygen that normally help clouds to cool and condense, was thought to form only colossal, short-lived stars. No one knows how this anomalous object managed to form – perhaps it was a fragment spun off during the birth of a supergiant star, back in the dark ages of the universe.

Now you see them...

Among the many faint companions of the Milky Way (see "Disappearing dwarfs", page 65) are two shining exceptions. The large and small Magellanic clouds are by far the largest of our dwarf-galaxy entourage. They are complex and active places where bright young stars are being born and others die, as the most recent nearby supernova, which occurred in the Large Magellanic Cloud in 1987, revealed.

That is all well and good – except that these galaxies might not be our satellites at all.

Observations in 2006 by the Hubble Space Telescope showed that these two dwarfs are crawling across the sky at a little shy of a millionth of a degree per year. That might not sound speedy, but the galaxies are more than 150,000 light years away, so this slow movement translates to a velocity of more than 100 kilometres per second. That might be too fast for the clouds to be held by the Milky Way's gravity.

Whether it is too fast or not depends on our galaxy's total mass. Most of the Milky Way's mass is thought to reside in its surrounding halo of dark matter, which stretches far beyond the bright disc of stars. The best way to estimate the mass of the whole galaxy is by following the motions of other, smaller satellite galaxies that are more conclusively in orbit, to see how they respond to our gravity. But these objects are fainter and slower than the Magellanic clouds, making them even harder to catch in motion. Taken all together, our most accurate estimates suggest the Milky Way has a mass somewhere between one trillion and three trillion times that of the sun.

That allows three possibilities. If the mass is near the top end of the range, then we should easily hold onto the Magellanic clouds, and they have probably orbited the Milky Way a couple of times since it formed. If it is somewhere in the middle, the clouds are likely to be making their first close approach to us. Over a few hundred million years they will begin to head further away, but they will return to us eventually, like a comet on an elongated orbit. If the Milky Way is right at the lightweight end of the scale, however, then the Magellanic clouds are just passing, and we will eventually have to wave goodbye to this charismatic pair of space tourists. ■

Earth odyssey

Our planet has faced many dangers on its epic journey around the galaxy. But what Earth has forgotten, the moon might remember, says **Stephen Battersby**

FOR billions of years, Earth has been on a perilous journey through space. As our planet whirls around the sun, the whole solar system undertakes a far grander voyage, circling our island universe every 200 million years. Weaving our way through the disc of the Milky Way, we have drifted through brilliant spiral arms, braved the Stygian darkness of dense nebulae, and witnessed the spectacular death of giant stars.

Many of these marvels may well have been deadly, raining lethal radiation onto Earth's surface or hurling huge missiles into our path. Some may have wiped out swathes of life, smashed up continents or turned the planet to ice. Others may have been more benign, perhaps even sowing the seeds of life.

As yet, this is guesswork. We cannot retrace our path through the galaxy's gravitational melee, still less calculate what incidents befell us where and when. Earth itself, its rocks constantly recycled by plate tectonics and remodelled by erosion, is remarkably forgetful of past assaults from space.

But a repository of our cosmic memories might be close at hand. The moon's soil and rocks endure undisturbed for aeons. Deep under the lunar surface there could lie an archive of our planet's voyage. What Earth forgets, the moon remembers.

A long time ago, in this galaxy but far, far away... the sky is packed with bright stars and glowing nebulae, far denser than today's tame heavens. But this scene is not to last. A great curving wave of stars picks up the solar system like a scrap of flotsam, sweeping it out into the empty galactic fringes, far from its forgotten homeland.

Today, the solar system travels a near-circular path around our galaxy, keeping a constant 30,000 light years between us and the seething galactic core. We once assumed most stars stayed in such quiet orbits for their entire lives. Our ride may have been more exciting. The characteristic spiral arms of a galaxy such as the Milky Way are waves of higher density, regions where stars and gas are a little closer together than elsewhere in our galaxy's disc. Their additional gravity is normally too weak to alter a star's path by much, but if the star's orbital speed happens to match the speed at which the spiral arm is itself rotating, then the extra force has more time to take effect. "It's like surfers on the ocean – if they're paddling too slow or too fast they don't get anywhere. They have to match the speed just right, then they get pushed along," says Rok Roskar of the University of Zurich, Switzerland.

Roskar's simulations show that a lucky star can ride the wave for 10,000 light years or more. Our sun may be such a surfer. Some measurements imply the sun is richer in heavy elements than the average star in our neighbourhood, suggesting it was born in the busy central zone of the galaxy, where stellar winds and exploding stars enrich the cosmic brew more than in the galactic suburbs. The gravitational buffeting the solar system received then might also explain why Sedna, a large iceball in the extremities of the solar system, travels on a puzzling, enormously elongated orbit.

This is mere circumstantial evidence. But we might find more direct traces of disturbing incidents from the distant past...

The sky blossoms with brilliant, blue-white young stars, some still cocooned in a gauze of the gas from which they formed. The brightest shines with the light of 20,000 suns, but its brilliance is a warning sign. Soon the star will explode, banishing the night for several weeks. Unlike the life-giving warmth of the sun, this light will bring death.

In a nearby spiral arm of the Milky Way, more than 1000 light years away from our solar system's present position, lies the Orion nebula, a birthplace of giant stars. Our solar system must at times have drifted much closer to such stellar nurseries. To do so is to flirt with disaster. A massive star burns its fuel rapidly, and in a few million years its core can collapse, unleashing the vast energy of a supernova.

X-rays from a supernova just tens of light years away could deplete or destroy Earth's ozone layer, letting in harmful ultraviolet rays from the sun. High-energy protons, or cosmic rays, would continue to bombard Earth for ›

GALACTIC JOURNEY

While our solar system circuits the Milky Way, our galaxy is itself flying through intergalactic space at more than 150 kilometres per second towards the nearby Virgo cluster. That space is sparsely populated with ionised hydrogen and helium, with a few tens to hundreds of particles per cubic metre. The galaxy's motion creates a huge bow shock in this plasma, capable of accelerating some of these hydrogen ions to lethal energies.

Magnetic fields in the galactic disc protect us from most such cosmic rays, but perhaps this has not always been so. As the solar system circles around the galaxy, it also bobs up and down through the galactic disc roughly every 60 million years, straying to either side by as much as 200 light years.

Adrian Melott of the University of Kansas in Lawrence has calculated that the cosmic-ray dose should be much higher on the northern side of the galactic plane beneath the bow shock. That could explain a controversial pattern in Earth's fossil record. In 2005, Robert Rohde and Richard Muller of the University of California, Berkeley, found that the diversity of marine fossils seems to dip on a similar timescale of 60 million years or so.

Lunar cosmic-ray records could be used to test that idea. If it stands up to scrutiny, then times could be bad for anything left on Earth in a few million years: the sun is already north of the plane, and heading deeper into danger.

decades, depleting ozone, damaging living tissue and possibly seeding clouds to spark climate change. Such convulsions might have triggered some of the mass extinctions that so cruelly punctuate the history of life on Earth – perhaps even hastening the demise of the dinosaurs 65 million years ago, according to a theory formulated in the 1990s.

Evidence for past supernovae is thin on the ground, although in 1999 German researchers found traces of iron-60 in south Pacific sediments. This isotope, with a half-life of 2.6 million years, is not made in significant quantities by any process on Earth, but is expelled by supernovae. The interpretation is disputed, but if iron-60 is a supernova's dirty footprint, it suggests a star exploded only a few million years ago within about 100 light years of us.

Planetary scientist Ian Crawford of Birkbeck, University of London, suggests we can look to the moon to find clear evidence of such astro-catastrophes. "The moon is a giant sponge soaking up everything thrown at it as we go around the galaxy," he says. Cosmic rays from a supernova will plough into the moon, leaving trails of damage in surface minerals that will be visible under a microscope and knocking atoms about to create exotic isotopes such as krypton-83 and xenon-126.

Although lunar soil is durable, over billions of years a constant rain of cosmic rays would obscure records of single events, even those as extreme as a nearby supernova. Crawford, together with Katherine Joy, formerly at the Lunar and Planetary Institute in Houston, Texas, and colleagues, thinks the trick will be to look for those relatively rare sites with a sequence of lava flows. When molten rock oozes out onto the surface and cools, it starts to collect traces of cosmic rays; if it is then covered over, it preserves a pristine record of the time it was exposed. Lava flows can be dated precisely by measuring the decay products of radioactive elements within them.

Spacecraft have already spotted plenty of tempting lunar lava flows. So far they all date back more than a billion years, to a time when the moon was hotter and so more volcanically active. Crawford hopes to find smaller, more recent lava stacks, or layers of rock melted by large impacts. Buried within may be records of supernovae that we can compare with Earth's fossil record to see if they match up with a mass extinction. Much more ancient rocks could tell us whether nearby supernovae were more frequent in the past – perhaps a sign that we once travelled through the denser, more eventful inner reaches of the galaxy.

> "The moon is a giant sponge soaking up everything thrown at it as we go around the galaxy"

And the moon may hold other memories…

The darkness is coming. It starts with just a small patch of starless black, but slowly grows until it blots out the sky. For half a million years, the sun is the only visible star. As alien dust and gas rains down and pervades our atmosphere, Earth is swathed in white cloud and gripped with ice; a pale mirror to the dark cosmic cloud bank above.

Interstellar gas permeates the Milky Way, but not evenly. The solar system happens now to inhabit an unusually empty patch of space, the local bubble, with only one hydrogen atom per five cubic centimetres of space. In the past we must have drifted through much denser gas clouds, including some more than 100 light years across in whose cold and dark interiors hydrogen forms itself into molecules.

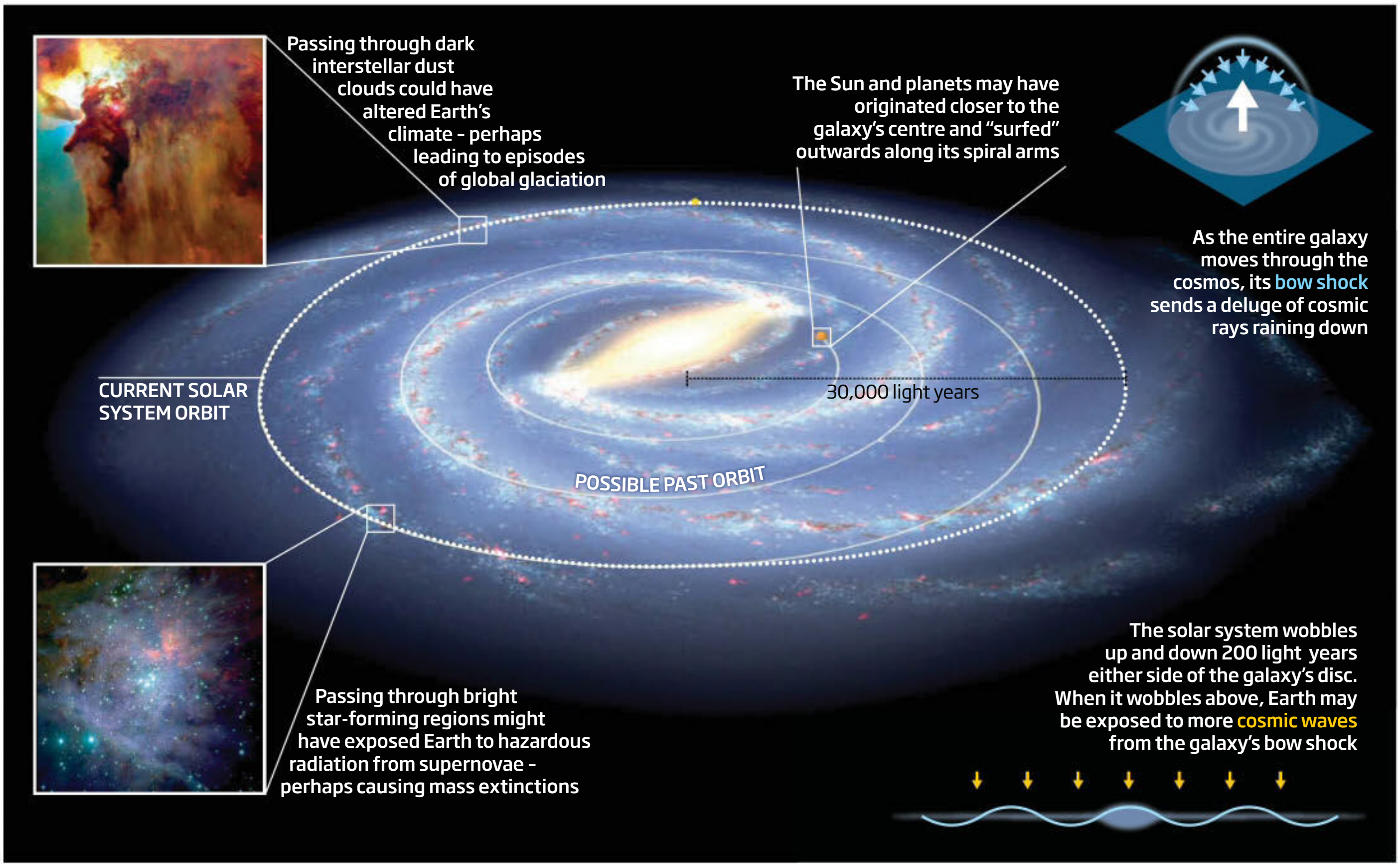
In such nebulae, Earth may have caught a cold. Usually, the solar system's interior is protected from harsh interstellar radiation by the solar wind, a stream of charged particles that flows deep into space, forming a huge electromagnetic shield called the heliosphere. When the interstellar gas gets denser, the solar wind can't push as far, and the heliosphere shrinks. Above a density of around 1000 molecules per cubic centimetre, it will contract to within Earth's orbit. That might happen every few hundred million years.

The accumulation of hydrogen in Earth's high atmosphere would alter its chemistry, creating a reflective cloud layer, while dust could mimic the shading effect of sulphate aerosols from volcanic eruptions. Alex Pavlov of the University of Colorado, Boulder, says the dust alone could trigger a global ice age, or "snowball Earth".

We know Earth has suffered such episodes, including big chills some 650 and 700 million years ago. Their cause remains obscure. It

Our way through the Milky Way

The solar system is travelling at a steady 220 kilometres per second in a circular orbit around the centre of the galaxy – but it might not always have done so



NASA

could have been the weathering of mountains that pulled carbon dioxide from the air, or volcanic eruptions, or changes to Earth's orbit around the sun – or a black cloud in space.

Then again, clouds may have had a happier influence on Earth. William Napier of the University of Buckingham in the UK has suggested that they could be staging posts for life, sheltering micro-organisms from cosmic rays and sprinkling them on to any receptive planet as it passes through.

The moon could again tell us Earth's tale. Up there, alien dust would have settled down to mix with the lunar soil. It would have a distinctive chemical signature, with high levels of uranium-235 and other isotopes that are generated in supernovae and scattered through space. Ideally, the dust would be entombed beneath a handy lava flow.

Getting to it won't be easy. "We may need to sink a drill into an area known to have lots of lava flows," says Joy. Setting up a drilling rig on the moon is beyond our present capabilities, but Joy points out that lava layers are exposed in some impact crater walls and long grooves on the lunar surface called rilles. A robotic probe could abseil down a crater wall and scoop out trapped soil from between the lava flows, Crawford suggests.

That soil could also hold mineral fragments that chronicle another chapter in Earth's odyssey – a story of rocks and wreckage.

The faint red star seems harmless at first, a barely perceptible speck outshone by 10,000 other points of light. But it grows. In only a few thousand years, it waxes to become the brightest star in the sky. Out in the Oort cloud far beyond Pluto, giant balls of ice and rock begin to deviate from their delicately balanced orbits and move in towards the sun. Soon the skies teem with comets – ill omens for Earth.

The moon's pitted surface records aeons of bombardment. Apollo astronauts found many samples of ancient melted rock, revealing that around 4 billion years ago the inner solar system was being pelted with massive bodies.

This "late heavy bombardment" is thought to have been caused by movements of the outer planets Uranus and Neptune disturbing asteroids in the Kuiper belt, where Pluto resides. Incidents in our galactic odyssey would have unleashed other storms of comets and asteroids. Passing stars or dust clouds might have triggered a one-off spike in the bombardment. A more regular pattern of new crater formation could reflect a repeated encounter on our path around the galaxy – passing through a particularly dense and unchanging spiral arm, for example.

To find out we would need to visit a variety of surfaces, taking small rock samples to determine their ages, and then making a careful census of craters to see how the impact rate has fluctuated. Buried soils could help, says Joy. "We might find fragments that would tell us what type of asteroids or comets were hitting the moon."

For the moment, we can only look at the craggy face of our old companion and wonder what stories it has to tell. If the world's space agencies stick to their present plans, outlined in the 2011 *Global Exploration Roadmap*, "it ought to be possible to start accessing ancient deposits within a few decades," says Crawford. Then, perhaps, we can start to write the definitive version of Earth's epic odyssey. ■

Mapping the Milky Way

It's hard to get a handle on what's where in our galaxy – but the picture's getting clearer, says Ben Gilliland

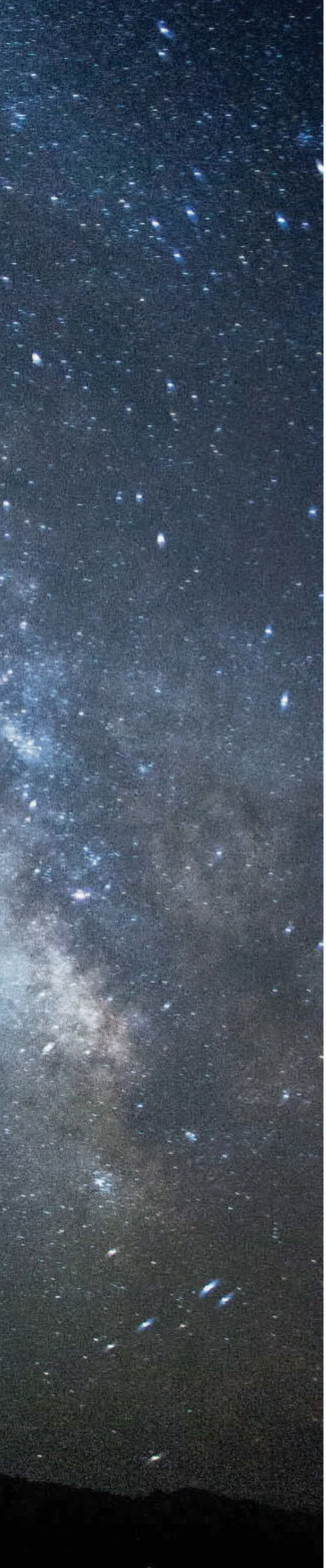
HUMANITY has made great strides in probing the grand mysteries of the cosmos. We have observed the afterglow of the big bang, spied on galaxies so distant we see them as they were when the universe was an infant, monitored far-off supernova explosions and penetrated to the very edge of a black hole.

One corner of the cosmos, though, has proved resistant to our attempts to get to grips with it: the bit we call home, the Milky Way.

With the Milky Way, we are inside the thing we are trying to observe. We can only dream of zipping outside our galaxy in a spaceship to get another perspective. So we must make do with our view from an insignificant blue blob orbiting one star out of many billions in a sprawling conurbation of stellar neighbourhoods.

It's not the best of views: from here the cosmic metropolis is obscured by a smog of dust and gas that fills up the space between the galaxy's stars. What's more, its districts are in constant motion, rotating at different speeds around the galactic centre.

Put that way, it seems miraculous we know much about the Milky Way at all. Yet slowly but surely we have begun to sketch a map of our galactic home.



WILLIAM CHURCH/GETTY

Picture of a galaxy

On a clear night, away from bright lights, you can see a hazy band of light bisecting the sky. The Romans called it "Via Lactea", or "Road of Milk" – the origin of our own Milky Way.

This strip of light gives us our first clues as to what our galaxy must look like from outside. It tells us we're not part of an unsculpted blob of stars, but instead somewhere inside a flattened disc looking towards the galaxy's dense, crowded heart (see "Bright lights, big city", below).

The Milky Way's closest galactic neighbour, Andromeda, is a flattened disc, too, with a distinctive spiral-armed appearance. Such structures form as clumps of stars and dust and are drawn together by gravity and begin to spin faster and faster around each other. As they do so, they are flattened down into a disc, rather as a pizza chef spins a dough ball to flatten it out. Any small disturbances in the motion or density of the disc's material bunch together over time, forming the spiral arms.

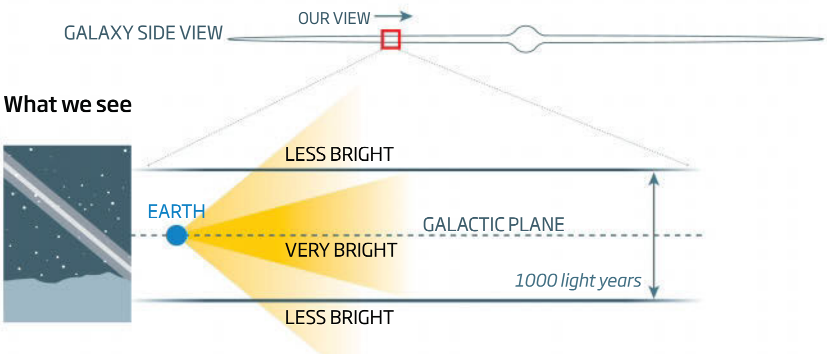
The advent of radio astronomy in the 1950s allowed astronomers to penetrate the fog of interstellar dust and begin to map the location and motion of similar denser structures within the Milky Way.

Over time, radio and infrared observations combined to create a picture of a galaxy not just with spiral arms, but also – unlike Andromeda, though like many other galaxies we see – a central, bright bar-shaped structure of stars.

The Milky Way's dimensions have been extrapolated by mapping groups of stars called globular clusters that hang out in the outermost galactic suburbs. At 100,000 light years across but only 1000 light years thick, our galaxy has about the same relative dimensions as a CD. We are now reasonably sure that we reside about halfway out – 25,000 light years from the galactic centre – in a region known as the Orion Arm.

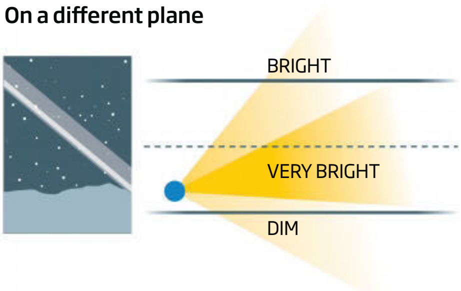
Bright lights, big city

The appearance of the Milky Way from Earth tells us a lot about our galaxy and our position within it



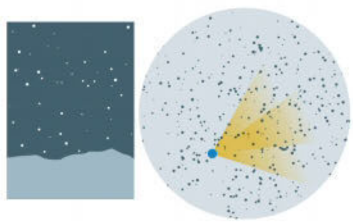
We see the Milky Way as a thin, symmetric bright strip across the sky. This tells us we are sitting in a thin disc of stars looking towards its centre, and seemingly close to the galactic plane

On a different plane

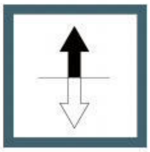


If we were significantly off the galactic plane we would see an asymmetric distribution of stars

Disc-free living



If the Milky Way were a sphere or other "3D" shape, we would see an equal distribution of stars all over the sky



Are we up or down?

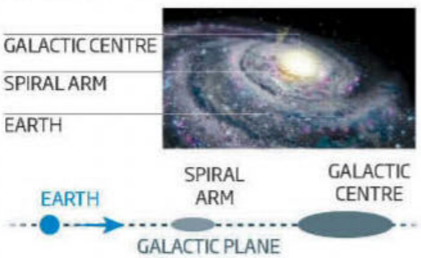
The effect of gravity in a disc-shaped galaxy like the Milky Way is to compress almost everything of interest into the central plane. From the symmetry of the Milky Way in the sky, there's good reason to believe that we are in that plane ourselves (see "Bright lights, big city", page 71). That's certainly been the official position since the 1950s: according to the International Astronomical Union's definition of the galactic plane, the sun lies directly within it. Ours is a frustrating ground-floor view of the galaxy.

In the past decade or so, though, studies using the ammonia emissions of dense, star-forming regions to assess their distance from us have suggested a different picture. The true galactic plane seems to be several light years lower than the IAU definition, with the sun 75 light years above it. The galactic centre is also about 20 light years lower than previously thought, placing the galaxy at a slight tilt relative to the sun's position (see "Penthouse view", below).

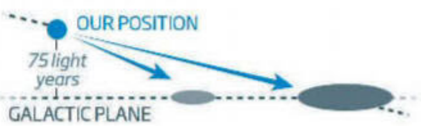
It's a small effect in a galaxy 1000 light years from top to bottom, but it makes all the difference. Rather than looking out of a ground-floor window at the galactic city, we may have a slightly elevated view of that crucial central plane from a few tens of storeys up.

Penthouse view

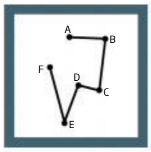
Most objects of interest in the Milky Way lie in or around the galactic plane – making our position relative to it crucial



The current assumption is that we are right in the plane, so have an obscured view of the galactic plane



New observations suggest we are actually slightly above the galactic plane – giving us a much better vantage point



What's where?

Observations of the Milky Way strip and our interactions with our galactic neighbours give us a reasonable idea of our galaxy's outward appearance and size. But how do we find out what's where within it? It's not easy: the night sky is a 2D projection of a 3D picture, with little indication of how far away different objects are.

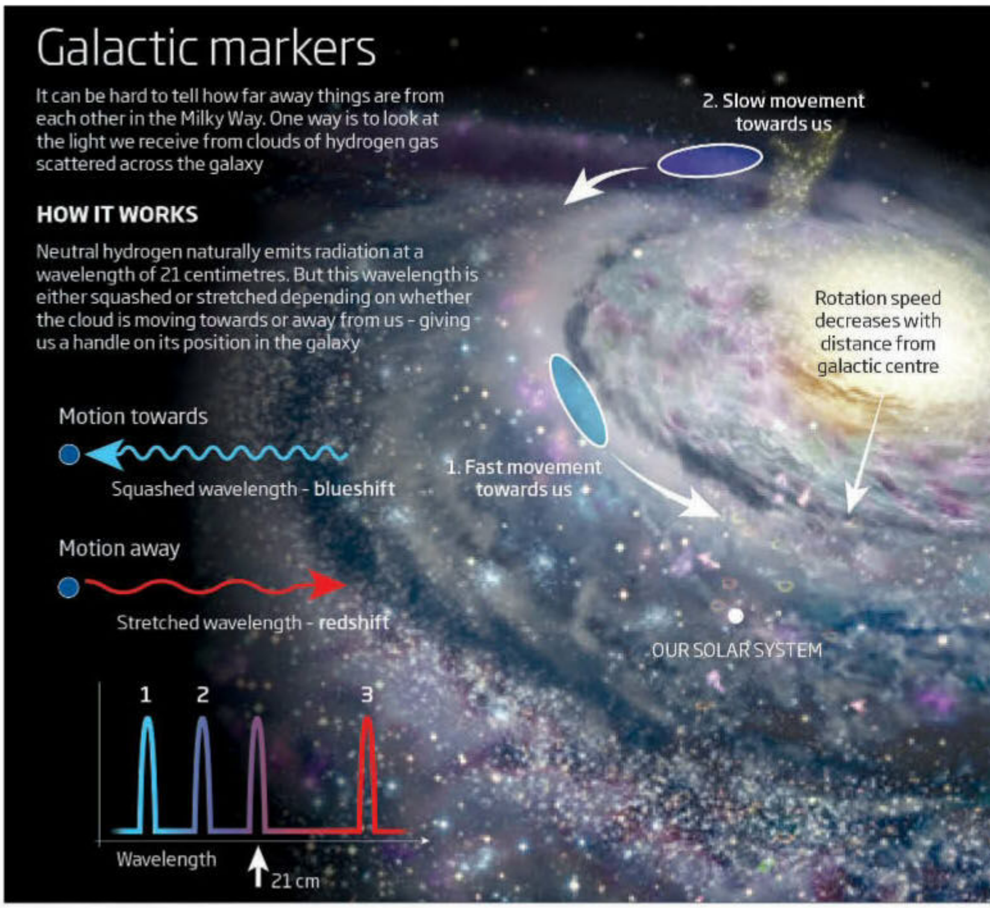
To get round this, astronomers turn to hydrogen, the most abundant element in the cosmos, accounting for 90 per cent of its non-dark-matter mass. Much of it lurks as vast, diffuse, faintly glowing clouds of neutral gas in the frigid space between stars.

The glow comes from photons emitted when slightly energised hydrogen atoms return to their natural, lowest energy. Sent out with a radio wavelength of 21 centimetres, this radiation isn't visible to the naked eye, but unlike visible light it can pass through dust and so make its way to Earth.

It's here that the Doppler effect kicks in. This effect, heard in the swooping tone of an ambulance siren as it passes us, describes how radiation is squeezed or stretched in wavelength depending on whether its source is moving towards or away from us.

In the galactic whirl, hydrogen clouds in different places will be moving at different speeds and in different directions relative to us. By measuring how the light we receive from them is shifted away from its nominal 21-centimetre wavelength, we can build up a 3D picture of those motions. Comparing the Doppler shifts of other objects to this reference then allows us to work out where in the galaxy they must be (see "Galactic markers", below).

Hydrogen's abundance means it provides only a rough "big picture" of the galactic movements. Emissions from less prevalent gases such as carbon monoxide and ammonia can be used in a similar way to pinpoint individual structures more precisely.



Weighing the Milky Way

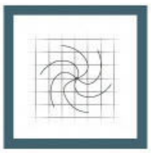
"Measurements confirm that the Milky Way's mass is far greater than can be accounted for by visible matter"

Our galactic neighbours can tell us something about how much stuff our galaxy must contain. Like all the nearby galaxies we see, the Milky Way is surrounded by a coterie of dwarf companions. The speed at which they circle depends on the size of the central mass that swings them round.

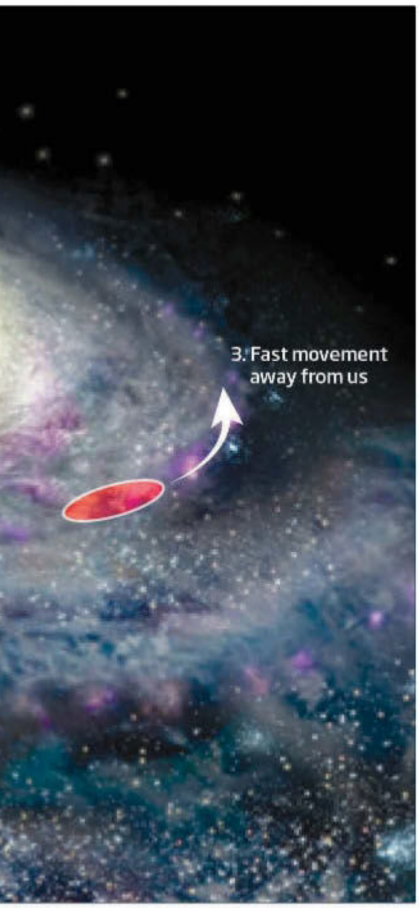
Measuring dwarf galaxy speeds confirms an effect seen in many other galaxies and clusters: the Milky Way's mass is far greater than can be accounted for by visible matter. About 90 per cent seems to take the form of some inscrutable dark" matter, whose identity remains one of the most pressing questions in physics.

The earliest estimates suggested the Milky Way's mass was about the same as, or perhaps even greater than, that of our nearest neighbour Andromeda – a puzzling result, as the Milky Way doesn't seem to have quite the number of dwarf satellites expected for that gravitational heft.

In 2014, however, a new "big picture" analysis by Jorge Peñarrubia at the Royal Observatory in Edinburgh, UK, and his colleagues took into account motions within the Local Group of galaxies, the imaginatively named cluster containing the Milky Way, Andromeda and a few others. Its conclusion was that the Milky Way has perhaps only half the mass of its neighbour – although at around 800 billion suns, it is still no lightweight.



The Milky Way's bones



PIKAIA IMAGING

Like radio emissions from neutral hydrogen, infrared radiation produced by the Milky Way's warm stuff pierces our galaxy's dusty fog. This has allowed instruments such as NASA's infrared Spitzer Space Telescope to infer the existence of networks of filaments underlying and jutting between the star-rich spiral arms of other galaxies – a skeleton of star-forming "bones". The bones themselves aren't visible: they are so dense the infrared radiation can't get through. But they are surrounded by a less dense "flesh" whose glow can be picked up.

Astronomers had long assumed that the Milky Way possessed similar structures as well, but until recently they had evaded detection, swamped in the galaxy's general infrared noise. But with care, the backlighting provided by the galactic centre allows us to view the bones directly – as infrared-blocking silhouettes.

"Nessie" is one prominent example: a serpent-like dark cloud first discovered in 2010. It was initially thought to be 260 light years long by 1.5 light years wide, and contain material with enough mass to outweigh 100,000 suns. More recently, however, Alyssa Goodman of the Harvard-Smithsonian Center for Astrophysics found it was just part of a larger structure somewhere between two and five times as long.

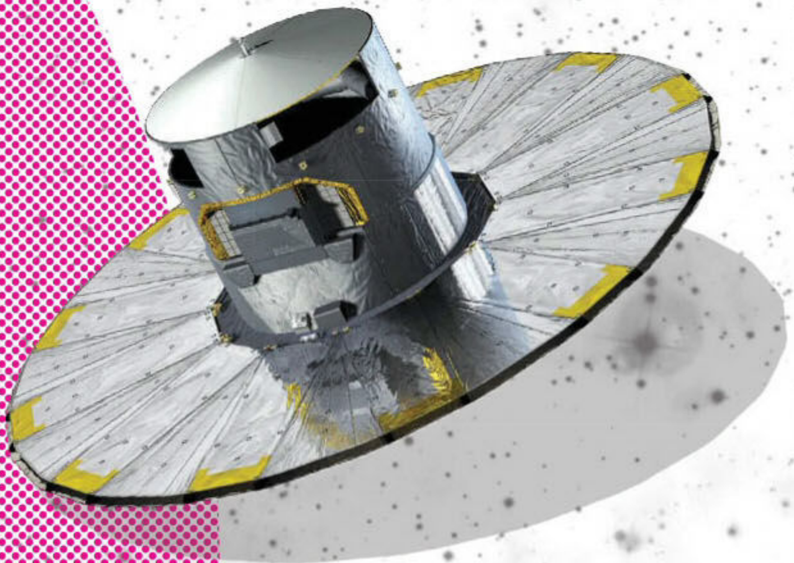
Mapping Nessie's three-dimensional position using latitude, longitude and velocity data from its carbon monoxide and ammonia emissions, and combining this with the redefined level of the galactic plane (see "Are we up or down?", page 72), suggests it lies on the galactic plane about 10,000 light years from the sun. It also implies it lives on and right along the spine of the Scutum-Centaurus arm, the closest major spiral arm to the sun looking towards the galactic centre (see diagram, page 64).

Such a long, filamentary structure would be expected to be extremely unstable and short-lived, suggesting Nessie is part of a much larger galaxy-scale structure. Even based on the most optimistic estimate of Nessie's size, it accounts for just five-millionths of the non-dark-matter mass of the Milky Way. Thousands more Nessie-like features in the galactic plane could be waiting to be discovered.

From our newfound position overlooking the galactic plane, the next few years should allow us to unearth more and more of these bones of the Milky Way. At the same time, the European Space Agency's Gaia mission, launched in 2013, will be mapping 1 billion of our galaxy's brightest stars – making for an unprecedented view of our galactic home (see "Top of the charts", page 74). ■

TOP *of the* CHARTS

We're about to get the most stunningly detailed map yet of our cosmic neighbourhood, says **Stuart Clark**



IT WILL be the biggest selfie of all time. When the Gaia space telescope completes its mission in 2018, it will have mapped a billion stars in our galaxy with unprecedented accuracy – and fundamentally transformed our understanding of the cosmos around us.

The European Space Agency's bold mission blasted off from French Guiana on a Russian Soyuz rocket on 19 December 2013. From there it travelled 1.5 million kilometres into space, spinning in a slow orbit around the sun, capturing every celestial object that falls within its gaze. As well as charting 1 per cent of the stars in the Milky Way – around one billion of them – the telescope will locate planets around other suns, warn us of asteroids in our solar system and pinpoint hundreds of thousands of new and distant galaxies beyond our Milky Way. It is a journey of discovery. "Gaia is going to revolutionise astronomy and I don't say that lightly," says Peter Allan of the Rutherford Appleton Laboratory in Didcot, UK, who is part of the Gaia team.

An accurate map of the heavens is a powerful thing. The one made by Gaia's predecessor, Hipparcos – which plotted the positions of more than 2.5 million stars between 1989 and 1993 – spawned thousands of papers on everything from the frequency of Earth's ice ages based on the sun's passage through the galaxy, to the dynamics of star clusters and the use of gamma-ray bursts in the search for extraterrestrial intelligence.

Hipparcos is a reminder that we have been charting the stars for more than 2000 years. The mission was named after Hipparchus, the Greek astronomer who lived from 190 BC to 120 BC and compiled the positions of around 850 stars visible to the naked eye. His star catalogue was not significantly bettered until the great celestial chart compiled by the Danish nobleman Tycho Brahe in the 16th century, decades before the invention of the ›

telescope. Between 1576 and 1597, using just sextants and armillary spheres, Brahe and cohorts of visiting astronomers mapped over 1000 stars at Uraniborg, his grand observatory on Hven island between Denmark and Sweden.

Celestial selfie

The invention of the telescope shortly after Brahe's death in 1601 brought further advances in the centuries that followed (see timeline, page 75). But Gaia's map will be in a different league. At the heart of the spacecraft is a 1-billion-pixel digital camera, the largest ever flown into space. It is stable and sensitive enough to see objects 400,000 times fainter than the dimmest ones visible to the naked eye, allowing us to create the truest representation of our galaxy yet.

At 100,000 light years across, the Milky Way is so vast that it is impossible for us to get outside it and photograph it from there (see "Mapping the milky way", page 70). Despite this, previous observations have allowed us to figure out that the sun lies three-fifths of the way from the galaxy's centre to its edge. They have also shown that our galaxy is a flat disc of stars, shot through with spiral arms of brighter stars. Gaia will pinpoint giant stars across most of the galaxy, even beyond its centre, where dust clouds obscure the view of smaller or dimmer objects, and so reveal the full details of their arrangement. "Gaia will let us build a picture of our own galaxy for the very first time," says the project's lead scientist Timo Prusti.

But it is not only the positions of the objects that are important – the way they move will help explain how our galaxy formed. English astronomer Edmond Halley first noticed the movement of the stars in 1718 when comparing his own measurements for three stars – Arcturus, Sirius and Aldebaran – with those made by the ancient Greeks nearly two millennia before. Until then, the orbs of heaven had been referred to as the "fixed stars". Halley proved this was not the case, and it meant that astronomers could extract more from stars than just their positions and brightness: their speed and direction of travel could provide important clues about the galaxy at large.

"The Milky Way is the only galaxy that we can study star by star. If you can measure positions and velocities, you can understand

"The accuracy of Gaia's camera would allow it to pinpoint a flea on the moon"

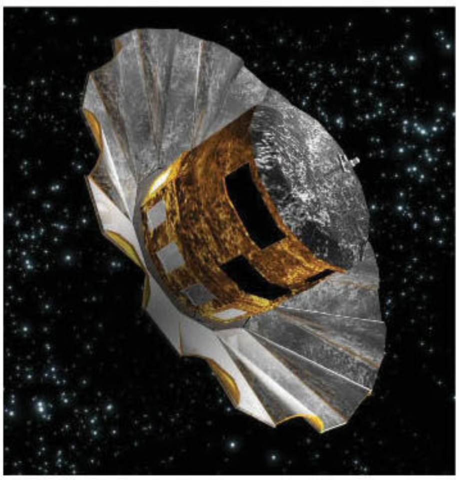
where all the forces are," says Mark Cropper, an astronomer at University College London who works on the Gaia project. These forces have shaped the galaxy for billions of years.

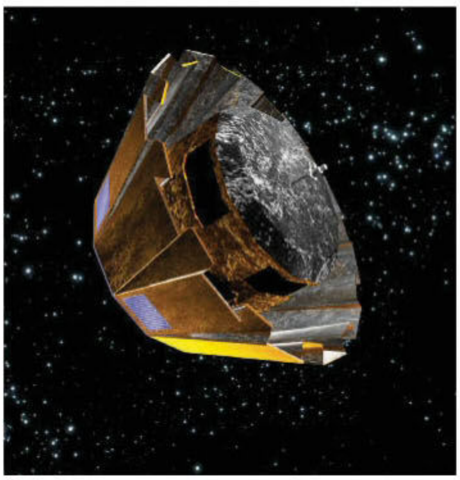
It is thought that large galaxies such as the Milky Way grow through a process of merging. The first stage sees several smaller galaxies collide and coalesce, but as this process progresses, one of the colliding galaxies can become very large. Gravity pulls the minnows into streams of stars, which become incorporated into the general rotation of the larger galaxy, leaving only the smallest hint of their previous motion.

Gaia's camera can pinpoint some stars to within a few millionths of an arcsecond – the equivalent of spotting a flea on the moon. By comparing observations over the five years of the mission, Gaia will be able to separate the stars into their respective streams on the basis of the similarity of their orbits around the galactic centre. This should reveal the remnants of the galaxies that have gone into making up the Milky Way.

Before Gaia, such galactic archaeology, as astronomers call it, was little more than a dream. Just a small handful of streams are currently known. Gaia's sensitivity is three orders of magnitude greater than any of its predecessors, says Cropper. "It allows much of the galaxy to be traced out and makes galactic archaeology possible. We will be catapulted into a new regime." That will tell us not only how our own galaxy formed, but will feed into our understanding of the evolution of the entire universe.

Similar searches might even reveal the sun's littermates (see "The sun's siblings", page 82). The sun was just one of hundreds of thousands of stars born 4.5 billion years ago when a cloud of gas collapsed in the Milky Way. Time and gravity were not kind to the newly formed star cluster. They tore it apart and scattered the other stars in the sun's litter far and wide across the galaxy. Despite this mayhem, sibling stars retain similar orbits to the sun – so Gaia's ability to track stars' movements could give us a chance of





By keeping itself cool with a sun shade, Gaia can spot faint objects

ESO/G. BECCARI

ESO/G. BECCARI

Gaia will chart 1 per cent of the Milky Way's hundreds of billions of stars

identifying them.

A star with the same orbital characteristics is still not conclusively a sibling. But Gaia has another trick up its sleeve to aid identification. It will split the light from the celestial objects it observes into a spectrum that allows a reasonable analysis of each star's composition. Because each gas cloud has its own chemical subtleties, the sun's siblings should all have identical chemical fingerprints. It is a needle in a haystack, but Cropper is optimistic: "If we put it all together, we may be able to identify the solar siblings even though by now they will be spread out all across the sky."

Gaia won't just help us to understand our own galaxy. It will also allow us to make more precise measurements of the phenomenon known as parallax, which is crucial to our wider understanding of the cosmos. "How accurately we gauge distance in the universe depends upon the precision to which we can measure the parallax distances to the nearest stars," says Prusti.

Every six months, Earth finds itself on opposite sides of its orbit around the sun. This movement of the planet means that the position of nearby stars appears to shift in relation to background stars that are further away. (It's the same effect you get when you look at a nearby object with one eye, then the other and see the image move.) The parallax is quantified by the angle of this shift. Once the parallax has been measured, it is possible to calculate the distance to the star using simple trigonometry.

The parallax angle is tiny, even for the nearest stars: less than 0.05 per cent of the diameter of the moon. Gaia's keen eye will be able to measure it for all 1 billion of the stars it will see. This is important because parallax distances are the foundation stone for the so-called cosmological distance ladder. This is a scale of inferences that allows us to estimate distances to further stars, which, in turn, allows the distances to be gauged to nearby galaxies, and then to more and more distant ones. Eventually, the scale reaches across the whole universe.

The more accurately we can measure the distance to a star using the cosmological distance ladder, the more accurately we will know its brightness, and so the amount of energy it is producing and what is going on inside it. The most important rung on the cosmological distance ladder is the first, because an error that creeps in here will affect all further rungs. More accurate distance measurements will also allow us to refine our understanding of dark energy, the mysterious force that is accelerating the expansion of the universe. "Gaia is going to get us out into the wider universe much more accurately than ever before," says Allan.

With so much riding on the mission, it is little wonder that Gaia has been decades in the

"The ability to track stars' movements could help us identify the ones born in the sun's litter"

making. It was first proposed in 1993, the year that Hipparcos stopped working, but it wasn't until 2006 that ESA began to build Gaia, whose price tag is a cool 650 million euros.

All the science depended on the launch going smoothly. And as anyone who has witnessed a launch will attest, the moment of ignition is always a heart-stopper. "It is only one moment in the mission but it is a pretty concrete moment," says Prusti, who was at the Kourou space port in French Guiana to witness the ascent. "It is a moment of silence when the mission walks a very thin line."

But if all goes well, Gaia will give us a whole new appreciation of the galaxy and the universe. "Gaia will show us all sorts of amazing and unexpected things," says Cropper. Which is more than you can say for most selfies. ■

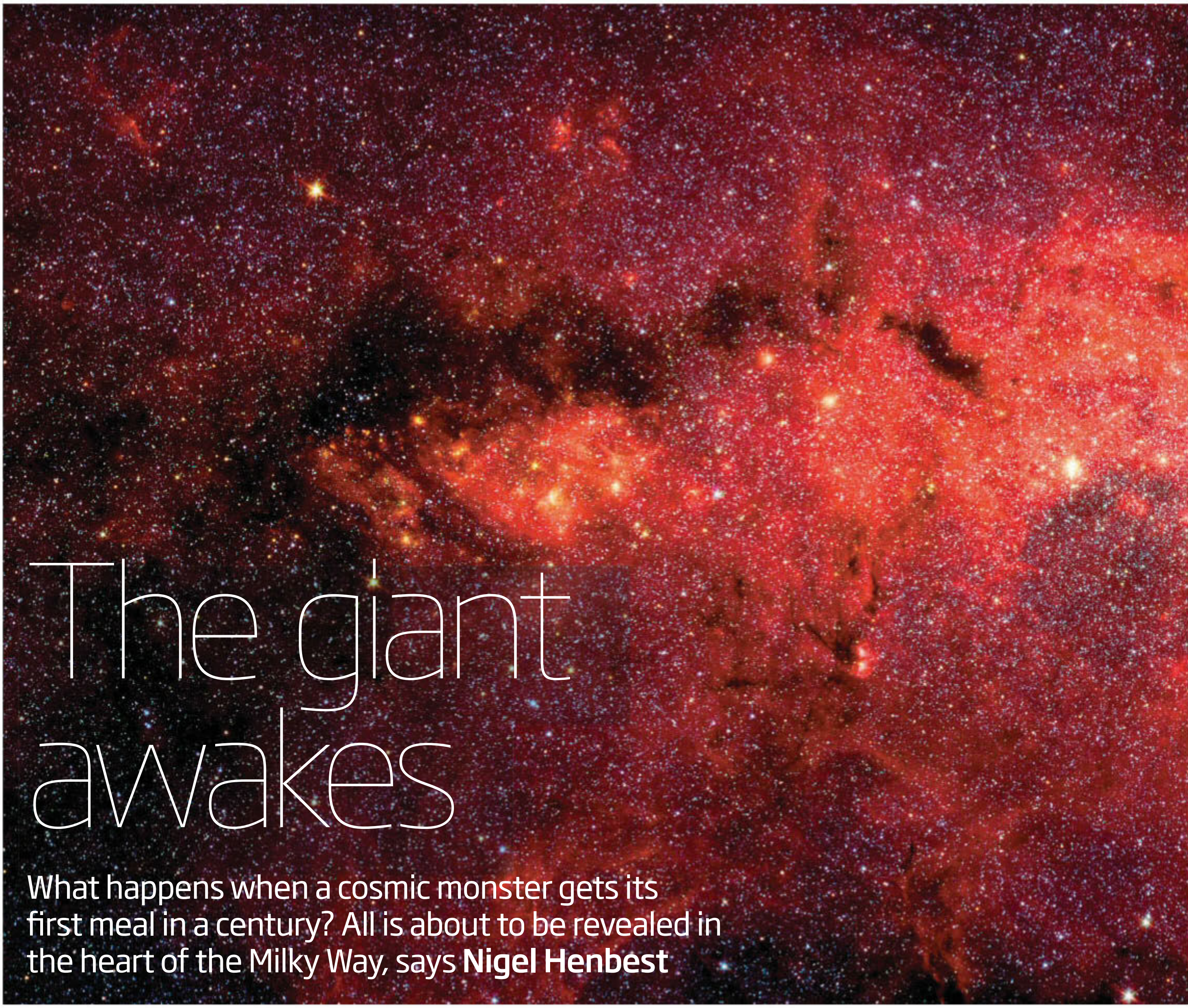
WOBBLY WORLDS

Astronomers estimate that Gaia will discover about 2000 planets around other stars. The spacecraft will not be able to see those planets directly because they are too small and dim. Instead, it will infer their presence by the effect they have on their central stars.

As the gravity of a mighty star pulls on a planet, the puny planet tugs back, causing the star to perform a small pirouette. Gaia will be able to measure these motions for stars within about 500 light years of Earth. Its haul of planets should span everything from Earth-size rocky worlds to gas giants like Jupiter and Saturn.

These planets aren't much bigger than the exoplanets discovered by NASA's Kepler mission. But Gaia will search "nearby" stars across the entire sky, rather than distant stars in a tiny patch of the galaxy as Kepler has done.

With astronomers currently planning missions to analyse the atmospheres of nearby planets, the resulting catalogue will be invaluable.



The giant awakes

What happens when a cosmic monster gets its first meal in a century? All is about to be revealed in the heart of the Milky Way, says Nigel Henbest

THE centre of our galaxy is a place of extremes. "It has the highest density of stars, the fastest-moving stars, the most concentrated reservoir of gas and the strongest magnetic fields in the galaxy," says Mark Morris, an astronomer at the University of California, Los Angeles. And lurking at its very heart is the most enigmatic object of all: our galaxy's very own supermassive black hole.

Known as Sagittarius A* – SgrA* for short – this dark presence whirls stars around at speeds approaching 20 million kilometres per hour, and is as massive as 4 million suns. Yet it is a docile monster. It merely snacks on the tenuous interstellar gas, which emits a faint glow of radio waves before disappearing into the gravitational maw.

But in the past, SgrA* has been responsible for mega eruptions that shaped the Milky Way into the galaxy it is today. Over the next few years, we are due to get our first glimpse of how a black hole springs into life, as a gas cloud called G2 nears its edge. It will give us an unprecedented insight into what makes a galaxy's dark heart tick.

It's not easy to study the Milky Way's centre. Vast quantities of dust absorb almost all the visible light emanating from it before it reaches Earth. If we dimmed our noonday sun by the same amount, it would appear fainter than the Pole star and the daytime sky would be unfathomably black. So to get a good view we must turn to radiation that penetrates the dust: radio, infrared and X-rays.

Observations from ground and space-based telescopes working at these wavelengths over the past couple of decades have revealed that SgrA* is, in cosmic terms, not a particularly outstanding beast. It is only 100 times brighter than the sun; a mere star such as Betelgeuse outshines the sun 100,000 times. Black holes can weigh in at billions of suns, with the gas falling into them heating and emitting radiation that can erupt as a quasar.

Discovered 53 years ago next month, quasars are the brightest objects in the universe. Their distance, however, makes them difficult to investigate. "Careful study of our own galactic centre, including the G2 encounter, is probably our best hope of understanding these phenomena in detail," says Daryl Haggard of Northwestern University in Evanston, Illinois.

Scientists have been studying G2 since 2012, when a number of researchers predicted fireworks as it made its closest approach. Instead, the cloud simply continued its slow

NASA/JPL-CALTECH/S.STOLOVY (SPITZER SCIENCE CENTER)/CALTECH

journey around SgrA*, prolonging its inevitable destruction.

But the years of observation have yielded intriguing new insights. Late in 2014, for example, NASA's Chandra X-ray Observatory detected X-ray bursts several hundred times brighter than normal emerging from SgrA*. Although the jury remains undecided, some astronomers have attributed them to G2's influence.

When similar, though less intense, bursts were observed in 2012, many pointed the finger at magnetic fields threading through the gas swirling around the black hole: as fields wind up tighter and tighter, sudden short circuits could produce brilliant flashes, like a flare on the sun. Alternatively, the fields might spin out of the gas disc altogether to produce a narrow jet of energy. Many quasars proudly display vast jets of energy that stretch thousands of light years, and the minor eruptions of SgrA* may be showing us how these jets are born.

Or perhaps they mean something else entirely. Sergei Nayakshin at the University of Leicester in the UK thinks the X-ray burst has all the hallmarks of coming from a lump of gas much smaller than G2 heated to 100 million degrees in the vicinity of the black hole.

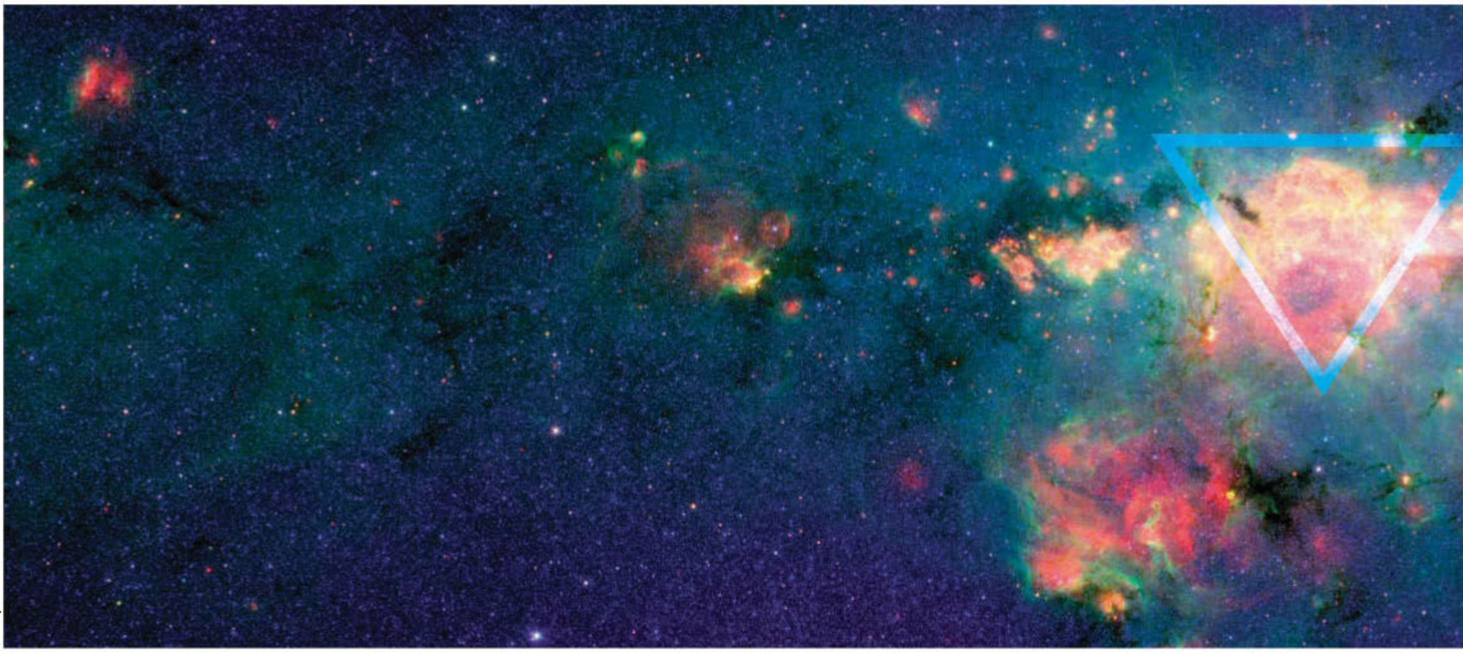
Doomed planets

His idea is that this blob of superheated gas is the remains of an ill-fated asteroid 10 kilometres across. Falling inwards from a huge cloud of space rocks that might surround the galactic centre, the asteroid swung past the black hole as closely as Earth orbits the

The bright spot at the heart of the Milky Way marks the maw of a giant black hole

sun, and was ripped apart by immense gravitational forces. "An asteroid's orbit can change if it ventures too close to a star or planet near SgrA*," says Nayakshin. "If it's thrown toward the black hole, it's doomed."

Every 100,000 years or so, Nayakshin reckons, an unlucky planet ends in the same way, in an even more spectacular blaze. Such a demise could account for an outburst of SgrA* as bright as a million suns a century ago, echoes of which still bounce around the galactic centre. Such echoes, in which radiation reflects off nearby gas clouds, were first discovered in visible light in the area around exploding stars, long after the original star had faded. Two X-ray satellites have monitored our ›


NASA/JPL-CALTECH

galactic centre over the past decade, and have seen a wave of X-ray brightness spreading across the cool gas clouds there. "We can work back from these observations to glean that a very powerful emission was coming from SgrA* as recently as 100 years ago," says Haggard.

At the moment, it's impossible to tell if this outburst was indeed the funeral pyre of a planet, or a giant magnetic burp. With future eruptions we should be able to tell, thanks to the imposingly named Event Horizon Telescope.

Seeing SgrA* in its most intimate detail requires the biggest possible telescope, and the Event Horizon Telescope fits the bill: it is a "virtual" telescope that links up radio dishes around the world, making it as wide as our planet. In its first outing, three linked radio observatories stared at SgrA* hard enough to make out a blob of gas right on the margin of the black hole, its event horizon. Now that extra radio dishes in Chile and Antarctica have been linked in, providing additional sensitivity, the telescope should be able to see if the outbursts of SgrA* are falling inwards – the mark of a disrupted asteroid or planet – or shooting outwards as a jet would.

The outburst 100 years ago was small beer on the scale of quasars, which can outshine a trillion suns. But further galactic archaeology has unearthed evidence of a more awesome outburst in the Milky Way's heart that pushed it to the edge of quasar brilliance. It comes in the form of two huge bubbles of hot gas that now tower 30,000 light years high on either side of the galaxy's centre (see diagram, below left). These "Fermi bubbles" were detected in 2010 by NASA's Fermi satellite, which picks out gamma rays from space. What could have inflated such vast structures?

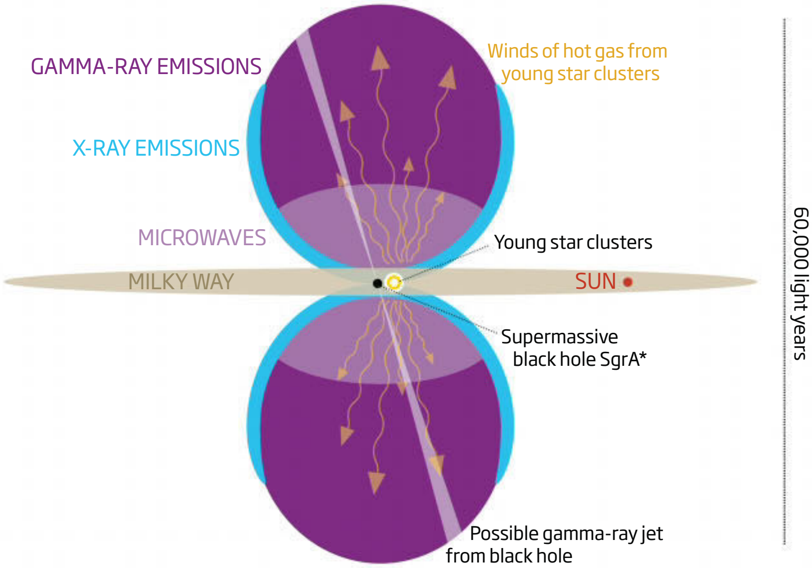
A clue comes from three clusters of massive young stars, one buzzing around SgrA* and two orbiting a little further out. One of the latter is the Quintuplet cluster, which contains the Pistol star, one of the most massive and luminous stars in the entire Milky Way. The birth of these clusters was a major event in itself and must have had wider ramifications. "Star formation is a very sloppy business, and 50 per cent of the gas would have been dumped onto SgrA*," says Farhad Yusef-Zadeh, also of Northwestern University. With a glut of gas to gorge itself on, SgrA* would have erupted with the power of 100 billion suns, making it shine like a quasar – albeit a mild-mannered one – and perhaps blowing the two huge bubbles of hot gas.

There are other explanations. "Everybody has a personal bias when it comes to the Fermi bubbles," says Yusuf-Zadeh. "Mine is that it is due to the energy of the starburst." But Fermi also shows tantalising hints of a straight "jet" within the bubbles that might mark a track of energy beaming out from the black hole to inflate the bubbles.

Whatever the details, the existence of the

Fermi bubbles

Vast bubbles of hot gas, extending 30,000 light years either side of the Milky Way, emit gamma rays, X-rays and microwave radiation. They may have been inflated by the emissions of young stars or by jets of energy from the black hole at the centre of our galaxy – or both



Fermi bubbles points to a huge disturbance at the galaxy's centre, with vast quantities of gas in motion, either falling into the black hole or collapsing to form the massive star clusters we see today. The quantity of gas is easy to explain: though there's little gas immediately around SgrA*, a few hundred light years out a necklace of huge, dense gas clouds orbits the galactic centre. One of these, known as SgrB2, weighs as much as 3 million suns, and contains over 100 different kinds of molecule, including enough alcohol to fill a glass the size of Earth. The question is how in the past similar clouds could have been kicked out of their stable orbits to form the new star clusters and feed the voracious SgrA* black hole.

Back in 2013, Kelly Holley-Bockelmann from Vanderbilt University in Nashville, Tennessee, and colleagues suggested that the culprit was a dwarf galaxy. As this interloper smashed into the Milky Way's heart, it squeezed gas clouds, causing them to collapse into a rash of bright new stars, including monsters like the Pistol star. The rest was dumped onto the central black hole.

Taking the plunge

Haggard has looked at twins of the Milky Way billions of light years away, and reckons such disturbances repeat over a galaxy's lifetime, perhaps every 10 to 100 million years. That suggests a long wait for the next "big one" – and means that astronomers are looking forward even more eagerly to events expected to unfold over the coming years.

Stefan Gillessen of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, found the gas cloud G2 while examining images of SgrA* that he and his colleagues had amassed over the past 10 years. It was a complete surprise, he says. Instead of orbiting the black hole at a safe distance, like its neighbouring high-speed stars, G2 is well into the danger zone. Gillessen's best bet is that the cloud was created by streams of gas from nearby stars, known as stellar winds, colliding and stalling.

"We could be witnessing a blighted solar system pass the black hole closer than Neptune orbits the sun"

Perhaps the most extreme suggestion describes G2 as gas boiling away from a system of planets forming around a young star. In that case, we are witnessing a blighted solar system swinging by a giant black hole more closely than Neptune orbits the sun – surely a scenario for a future science fiction movie.

Much more will be revealed as G2's orbit tightens later this year and some of its gas begins to be sucked in. "It's a great, great event," says Yusef-Zadeh. For a start, it will tell us something about the atmosphere of a black hole. If very little gas surrounds SgrA*, G2 will simply warm up as the black hole's gravity squeezes it into a long spaghetti-like shape. Infrared telescopes will see a surge in its brightness, but other instruments won't detect much at all.

On the other hand, if there's a so far undetected dense disc of gas tucked in closely around the black hole, G2 will generate a burst of X-rays and radio waves as it smashes through at high speed. The collision may even show if SgrA* is emitting a jet of energy too small for astronomers to have detected with ordinary telescopes.

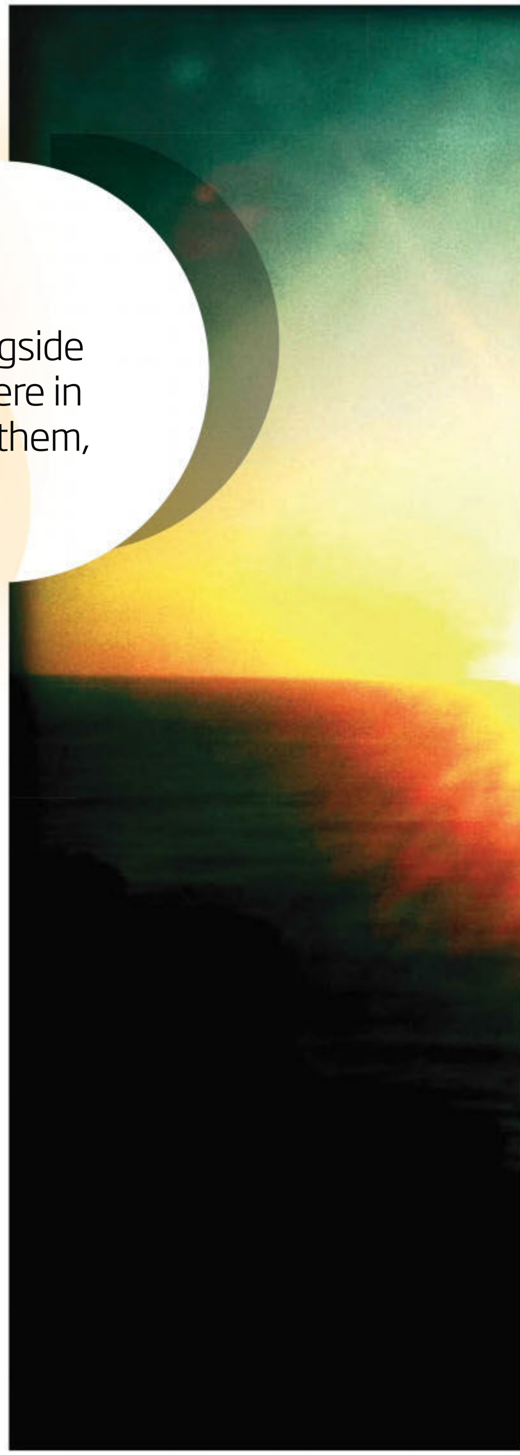
Gillessen and his colleagues started watching three years ago and expect to keep their eyes glued throughout 2016. Haggard, too, is in for the long haul. "The encounter between G2 and SgrA* could unfold over the course of several years – or even longer," she says. If the remains of the gas cloud swirl into a persistent disc around the black hole, we could even see a miniature version of a quasar, powering more serious jets shooting off into space.

Should we be worried? Probably not. G2 is a weakling on the galactic scene – it weighs only as much as three Earths – so no one is expecting a fully blown quasar to flare up in the galaxy's centre. An outburst of that size is perhaps 10 million years away, says Morris. Even then, it is unlikely that our descendants, if still on the scene, would need to head for the nearest bomb shelter. "While the explosions and quasar episodes that take place at the galactic centre are a fantastic opportunity for astronomers, they are very unlikely to have a major effect on Earth," says Morris. "At a distance of 25,000 light years, we are pretty far from the danger zone."

It would be quite a spectacle if we could make the 25,000-light-year trip to the galactic centre to see the action at first hand. "Our vision of the 'night-time' sky would be breathtaking," says Morris. "For every star we can see in the terrestrial sky, you would see a million." But with high levels of background radiation, and an uncertain monster lurking nearby, it is probably somewhere we would not want to consider going, says Yusef-Zadeh. "No way! I'm not crazy, I know what it would do to me and I value life too much." ■

The sun's siblings

Most of the stars born alongside the sun still shine somewhere in the Milky Way. Can we find them, asks **Ken Croswell**



OUR sun is a lonely star. Its light takes more than four years to travel through space to its nearest neighbour, Alpha Centauri. Yet this wasn't always the case. Turn the clock back 4.6 billion years and the same cloud of gas and dust that formed the sun also gave birth to a bunch of other stars: the sun's siblings.

The interstellar cloud that spawned the sun has long since vanished, but most of the stars born with it must still shine somewhere in the Milky Way. Now astronomers in Australia are gearing up to search the skies for them. "I'm utterly fascinated by anything historical," says Joss Bland-Hawthorn, a member of the search team at the University of Sydney, New South Wales. "I would love to know whether we can identify stars that were born with our sun." At stake is one of the key questions of our existence: how did the solar system produce a planet like ours? (see "How was the solar system built?", page 7)

Evidence that the sun was once part of a brood comes from the rubble leftover from the formation of the solar system. These primordial meteorites contain compounds that can only have formed from the decay of radioactive isotopes produced when a star explodes in a supernova. The abundance of such compounds tells us that the sun grew up less than 1 light year away from a massive star that exploded.

It gives away other information, too. Astronomers have observed that stars tend to form either in loose groups of a few dozen similar in mass to the sun and smaller, or in large clusters containing hundreds or thousands of stars spanning a wide range of masses. That meteorites contain the remains of a massive star therefore points to the sun's nursery being a large star cluster.

In 2010, Fred Adams at the University of Michigan in Ann Arbor reviewed all the properties that constrain the solar system's history and concluded that the sun's star cluster probably had at least 1000 members.

Sibling-hunters face a daunting task, though. The sun's brothers and sisters are a tiny minority in a galaxy with hundreds of billions of stars. And history has not been kind to them. Once a star cluster is born, it emerges into a galaxy that tries to tear it to shreds. Ironically, one of the first threats comes from the same giant clouds of gas and dust that create stars. The largest such clouds are millions of times more massive than the sun, and their gravity can hurl stars into the galaxy at large.

Exploding stars only add to the problem. A cluster is held together by gravity, so when an exploding star catapults material into space, the loss of mass weakens the cluster's grip on its members. That leaves it vulnerable to the galaxy's gravity, which pulls hardest on the stars closest to the galactic centre. Passing stars also tug at the cluster, their pull strong enough to lure individual stars away. Finally, interactions among cluster stars can eject the lightest ones.

After 4.6 billion years, the forces of galactic erosion have abraded the sun's birth cluster and scrambled its stars. They could be anywhere – including on the other side of the galaxy. Throw a drop of red dye into the ocean and look for the colour an hour later, and you have an idea of the size of the challenge.

The good news is that not all of the sun's siblings might be so far away. In 2009, Simon Portegies Zwart of Leiden University in the Netherlands carried out computer simulations of large star clusters to see where the sun's siblings might have ended up. He estimates that between 10 and 60 of them still reside within just 330 light years of us. From that distance, a star like the sun is visible through binoculars.

Not everyone is convinced by this tally. Yury Mishurov and Irina Acharova of the Southern Federal University in Rostov-on-Don, Russia, believed it was too optimistic. In 2010, they suggested that gravitational interactions with the Milky Way's spiral arms can also scatter a cluster's stars. Their own simulations suggest

PLAINPICTURE/KNIEL SYNNATZSCHKE

How many alien horizons enjoy a similar sunset?

that just a few siblings might remain nearby.

To find them, Bland-Hawthorn and his colleagues are pinning their hopes on a new instrument, called HERMES. Attached to the Anglo-Australian Telescope at Siding Spring Observatory near Coonabarabran, New South Wales, HERMES will look at the chemical make-up of more than a million stars up to 20,000 light years away.

Launched in 2014, HERMES is measuring the abundance of 25 chemical elements in every star it looks at, each of which tells a story about its star's origins. By using so many chemical elements, Bland-Hawthorn and his colleagues hope to find stars with a chemical make-up matching the sun's. "I wish I could tell you that it's going to be easy," says Bland-Hawthorn. "It's going to be a 10-year mission to try to crack this."

"Up to 60 of the sun's siblings could reside close enough to us to be visible through binoculars"

Even the results from HERMES may not be enough. According to the laws of motion, the sun's brothers and sisters should follow a similar course around the galaxy as the sun, despite galactic forces having tossed the stars around so much. To identify a true sibling, researchers will need to combine the chemical information about stars with measurements of their velocity made by the European Space Agency's Gaia spacecraft, which has been scanning the sky since 2013 (see "Top of the charts", page 74).

Data from Gaia will also shed light on the solar sibling candidate HD 162826, identified by Ivan Ramirez and his team at the University of Texas at Austin in 2014.

But we might not have to wait that long. APOGEE, a smaller survey at the Apache Point Observatory in New Mexico, aims to decipher the Milky Way's history by examining 100,000 stars. It will measure the abundances of 15 chemical elements and although it is not looking explicitly for the sun's siblings, "it's very possible that these stars will be in the sample", says Steven Majewski of the University of Virginia in Charlottesville.

One advantage of APOGEE is that 10 per cent of the stars it surveys are shared by NASA's Kepler spacecraft, whose observations of flickering starlight will tell us the ages of these stars. This is crucial, says Majewski, because any solar sibling must be the same age as the sun, as well as share its chemical composition and motion.

Finding them could help explain how a planet like ours came into existence. Perhaps a massive star in the sun's cluster exploded at just the right time and in just the right place to produce the conditions necessary to build a life-supporting planet. Other stars in the sun's cluster may have helped too, their radiation and gravitational tugs sculpting the nascent solar system.

The sun may have returned the favour. If its cluster had a thousand stars, then about 40 should be similar in size, temperature and luminosity to the sun. Perhaps they have planets supporting intelligent life, too. Residents of a distant planet may have already recognised their kinship with our sun, whose light and gravity could have helped their solar system prosper 4.6 billion years ago. ■

WORLDS OF PURE IMAGINATION

Astronomers are hunting exoplanets weirder than any spotted before. **Adam Hadhazy** *introduces five alien worlds just over the horizon*

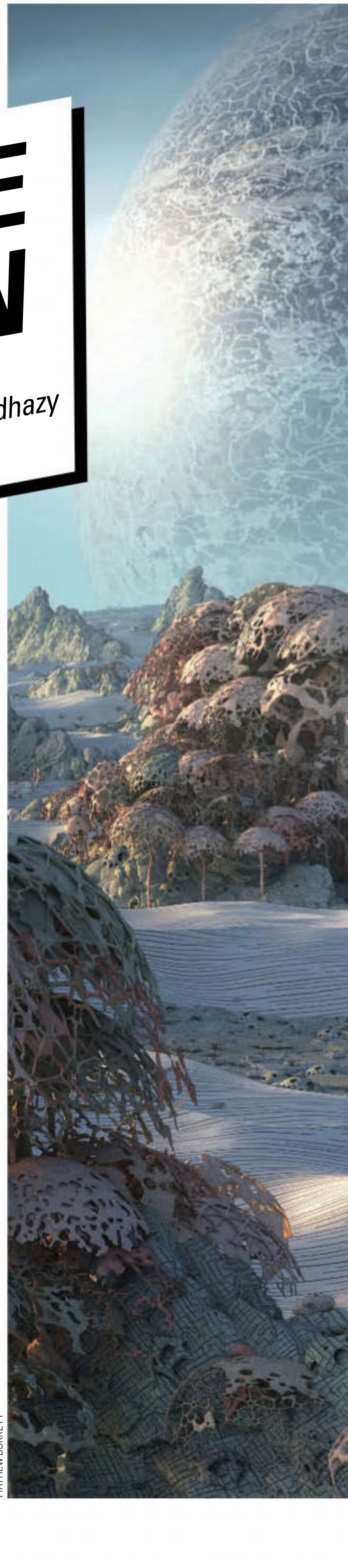
UP UNTIL the mid-1990s, the only planets whose existence we knew about for certain were those in our own solar system. This narrow view was changed when the first exoplanets were found orbiting around pulsars – the burnt cinders of exploded stars – swiftly followed by the discovery of gaseous titans in searing proximity to their suns. In the best traditions of exploration, these foreign planets were unlike anything astronomers had previously imagined.

The variety of exoplanets bagged since then has only pushed the envelope further. Exoplanets, we have learned, are happy to bask in the simultaneous light of four suns, wander the galaxy as starless outcasts from their home solar systems or orbit whipper-snapper stars barely 1 million years old.

"What happened in our solar system hasn't served us very well in predicting what we will find around other stars," says Gregory Laughlin of the University of California, Santa Cruz. "We expected planets like we have here, but we've been continually surprised."

With more exoplanets discovered in the past few years than at any time before, and the haul now over 2000, astronomers wager there are plenty more surprises in store. Naive theories of what extrasolar worlds should be like have been consistently overturned by the data, says Stefano Meschiari of the McDonald Observatory at the University of Texas at Austin. "We really didn't know the extent of the diversity of exoplanets and configurations until we actually observed them."

In an attempt to steal a march on nature, researchers are now busy imagining weird new types of exoplanet that might turn up in future. Far from being a parlour game for bored astronomers, understanding nature's ability to produce planetary bodies of all kinds will be crucial to learning how our solar system compares to its galactic counterparts. Many of these proposed exoplanets challenge our understanding of planet formation, and could play havoc with our admittedly arbitrary criteria for determining what constitutes a planet in the first place. Furthermore, exotic new planetary types should expand our inevitably Earth-centric ideas about where habitable planets might form, aiding in the search for alien life (see "Ideal homes", page 89). Here are five of the zaniest exoplanet types that could shake things up in the years to come.



MATHEW BORRETT

P1 BINARY WORLDS

PLANETARY DOUBLE ACTS ORBITING EACH OTHER IN A STATELY WALTZ

In our solar system, large planetary bodies are located far apart, orbited by moons of much smaller size. We think this familiar configuration emerges when bits of dust clump together in a protoplanetary disc encircling a young star, evolving into rocky hunks that hoover up any material in their orbital paths. Moons can then be crafted from leftover detritus orbiting the planet, or else be hauled in during the chaotic pinballing of objects thought to happen in developing solar systems.

There is a third option, however. Widely accepted models suggest our own moon formed when a Mars-like body – dubbed Theia – smacked into the primordial Earth, gouging out material that coalesced into the satellite we know today. But if those two bodies had undergone a less spectacular collision, they could have ended up in a stable partnership. "If you changed the nature of the encounter that led to our moon, then you might have gotten the binary planet outcome," says David Stevenson of the California Institute of Technology in Pasadena.

Finding binary planets could therefore shed light on the rambunctious childhood years of fledgling solar systems. It would also prove that collisions of the kind that created our moon can be considered a viable route to planethood, and not just a way to form satellite hangers-on. "It would tell us that at least in some cases, planet formation proceeds by the close encounter of large, similar-sized bodies," says Stevenson. Fortunately for astronomers, binary exoplanets should cast distinctive double shadows as they cross and partially eclipse the shining faces of their stars – so-called transit signals readily detectable by NASA's Kepler telescope and other observatories designed to look for new worlds.

Undoubtedly the most intriguing configuration would be two Earthlike worlds locked in a binary orbit. Imagine if Earth had a habitable twin in our sky, and if life, or even a technological, space-faring civilisation, arose there in parallel to our own. "Would the planets be at war?" asks Stevenson. "Makes for great science fiction."

P2 PARTY PLANETS

MULTIPLE WORLDS SHARING THE SAME ORBITAL PATH

Although the worlds in our solar system stick standoffishly to their own orbital lanes, they do tolerate company beyond their faithful moons. Asteroids dubbed Trojans, for instance, hang out at Lagrangian points, sweet spots where the gravitational force of a planet and its star balance out. These points move around the planet's orbit as it rotates, dragging their inhabitants along with them. Jupiter shepherds an army of Trojans around the sun, and Earth actually has a Trojan of its own, a tiny rock called 2010 TK7.

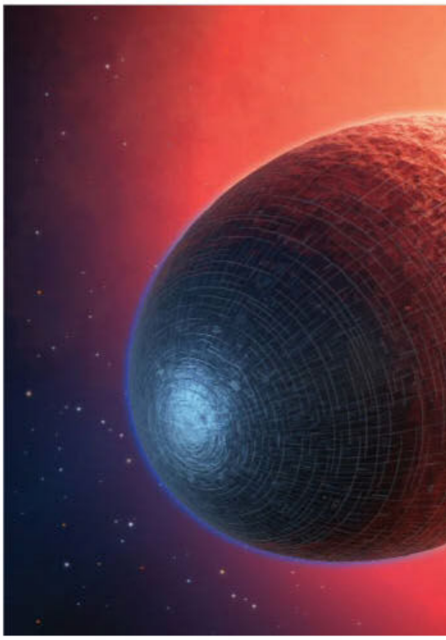
In theory, there is no reason why planet-sized objects couldn't also arrange themselves in such complex configurations. According to simulations by Gregory Laughlin of the University of California, Santa Cruz, and Stefano Meschiari of the University of Texas at Austin, multiple Earth-sized, habitable worlds might plausibly share a "party orbit", all at roughly similar distances from their host star. "It's not just two to tango," says Laughlin, "but three to four to five to six to tango."

Arrangements of this sort can be stable for billions of years – so long as there are no gravitationally perturbing worlds on either side of the crowded orbital band to disrupt its delicate choreography. "Planets with very similar orbital periods are totally possible," says Meschiari. What is less clear, however, is how the bulk of a solar system's planet-making material would gel into a tight-knit batch of worlds. The hard part is not so much guaranteeing orbital stability, he says, "but whether nature actually allows the formation of these planets."

Researchers on the Kepler telescope got ahead of themselves in 2011, when they reported spotting the signature of two planets with the same orbital period. Further analysis showed one of the pair in fact had a significantly longer year, consigning it to a completely separate orbit. Although continued Kepler analyses are still our best bet to spot planets of this kind, future transit missions such as NASA's Transiting Exoplanet Survey Satellite (TESS) or ESA's Planetary Transits and Oscillations of Stars (PLATO) may get lucky.

The existence of co-orbital planets would upend the current doctrine that planets must keep their orbital backyards free of other large bodies – something that ousted Pluto from the full-planet club in 2006. These worlds could even cross-pollinate, thanks to meteorite impacts blasting out rocks harbouring hardy bits of genetic material. "The planets would share a genetic lineage," says Laughlin, with their unique environments driving biology down alternate tracks. "Evolution would proceed differently on those two worlds."

"A PLANET IS LIKE A MELON - SQUEEZING IT CAN TEACH YOU ABOUT ITS INSIDES"

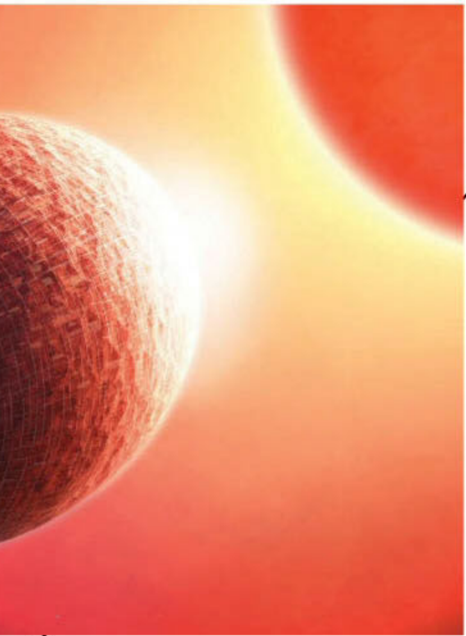


P3 EGG WORLDS

ROCKY PLANETS SQUEEZED INTO EXTREME SHAPES

The gaseous giant WASP-12b orbits its star at such scorchingly close quarters that the strong stellar gravitational pull has warped it into a bulging oval. Prabal Saxena, then at George Mason University in Fairfax, Virginia, and his colleagues decided to explore how this tidal distortion might affect a rocky world such as Earth. They calculated that an exoplanet of this kind could conceivably stretch to be a fifth wider at its equator than from pole-to-pole before being torn asunder by its star.

The discovery of rugby ball-shaped worlds could be a boon for planetary science. "Aspherical exoplanets have the potential to tell us a lot about planetary interiors," says Saxena. The way a planet responds to a star's gravitational pressure would provide an entirely new way of learning about its composition. Squeezing an object is a handy way to learn about its



insides, says Laughlin: "Like at the grocery store, with a melon or a grapefruit."

The planetary equivalent of gauging a melon's ripeness would be determining whether a planet is mostly solid or gaseous. As rocky planets are more likely to be habitable, measuring the ease with which a planet deforms would provide us with a way of determining its potential to harbour life, says Saxena. As a bonus, the atmospheres of ovoid worlds would experience different levels of gravity in different places, possibly making for intriguingly unpredictable climates.

Stay tuned, for these egg worlds might crop up in yet-to-be-processed data from NASA's Kepler telescope, or even be detected by space-based instruments such as TESS or huge ground-based telescopes scheduled to be built over the coming decade.

P4 | CHTHONIAN PLANETS

NAKED WORLDS WHOSE ATMOSPHERES HAVE BEEN BOILED AWAY

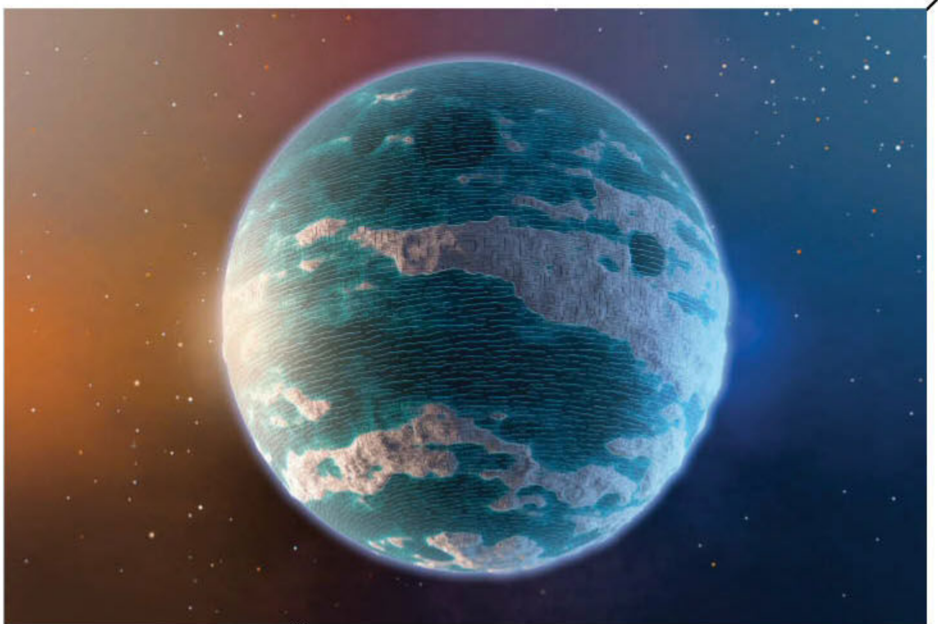
As solar systems evolve, the gravitational force planets exert on each other means they can slowly move inwards or outwards from their shared star. Called migration, this process helps explain the Milky Way's puzzling abundance of worlds the size of Neptune or Jupiter occupying star-hugging orbits. These massive exo-worlds must have formed further out, or else the star's radiation would have prevented their constituent materials from ever coalescing into a planet. Nudged towards a stellar furnace by migration, starlight withers away their atmospheres, eventually leaving nothing but their rocky cores. This exposure of the planet's hidden depths inspired the name chthonian, a reference to the deities of the Greek underworld.

There are broadly two types of scientifically valuable and potentially detectable chthonian planets. The first are habitable evaporated cores (HECs): cold, mini-Neptunes that migrate towards their stars' temperate, habitable zones. The extra stellar radiation they receive can blow off their atmospheres and even melt exposed surface layers of their rocky cores, which are rich in water ice. These planets could accordingly transform into ocean-covered worlds with life-friendly air, opening up a new avenue for the rise of alien life. "The surfaces of HECs used to be the gas-solid interface deep in the planet's interior – a rather hellish place indeed," says astrobiologist Rodrigo Luger of the University of Washington in Seattle. "But once the gas evaporates away, you're left with a surface that's potentially habitable."

The other interesting type of chthonian planet starts out more like Jupiter, the iconic gas giant of our solar system whose origins are still shrouded in mystery. Studying the rocky core of such an exoplanetary gas giant stripped bare by its star would accordingly give scientists valuable insight into the sequence of planetary formation. "If you expose the core, then you see what happened first," says Laughlin.

Catching the process of migration as it leads to atmosphere loss would be a valuable piece of evidence in favour of the chthonian planet theory. Intriguingly, Francesca Valsecchi of Northwestern University believes that the gaseous giant WASP-12b might be in just such an evolutionary phase: not only being squished by the gravity of its merciless star (see "Egg Worlds", left), but also having its atmosphere boiled away to nothing.

And as for the specific case of HECs, researchers believe their distinctively low densities suggests they migrated inwards from their solar system's distant outlands of ice and snow.



Wacky worlds

Yet-to-be-discovered exoplanets could have shapes and orbits unlike anything seen in our solar system

Binary worlds

Two planets of equal size, orbiting each other as they journey around a shared star

Party planets

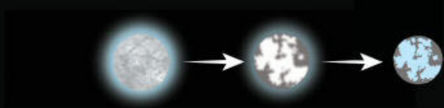
Multiple worlds occupying the same orbit, violating the conventional definition of a planet

Egg worlds

Rocky planets squeezed into highly eccentric shapes as a result of their star's strong gravitational pull

Chthonian planets

Habitable Evaporated Cores (HECs)

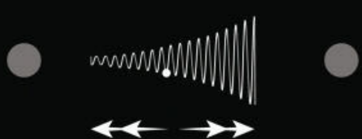


Gassy worlds born in a distant orbit that migrate towards their star. The sudden heat would evaporate their atmospheres, thawing their frozen cores into oceans capable of sustaining life

Exposed Cores

Gaseous giants pulled towards their stars, where their thick atmospheres are boiled away to expose their hidden, rocky cores

Corkscrew planets



Planets tracing a corkscrew orbit around the axis between two stars

P5 | CORKSCREW PLANETS

PRISONERS OF GRAVITY PING-PONGING BETWEEN TWO STARS

Even the craziest planets concocted by theorists still tend to trace conventionally near-circular orbits in a flat plane. Not so the corkscrew planet. Mind-bendingly, these worlds could exist in a sort of orbital limbo, spiralling about an axis between two stars in a binary system, pulled hither and thither by their competing gravities. The brainchild of theoretical physicist Eugene Oks of Auburn University in Alabama, these whirligig worlds represent a completely new type of stable, albeit speculative, planetary orbit.

Oks ran the numbers for a corkscrew planet pulled between the orange and red dwarf stars comprising Kepler-16, a binary system 200 light years from Earth. The planet would complete a manic loop-the-loop in its cone-shaped orbit in under an Earth week, straining our conventional definitions of a year.

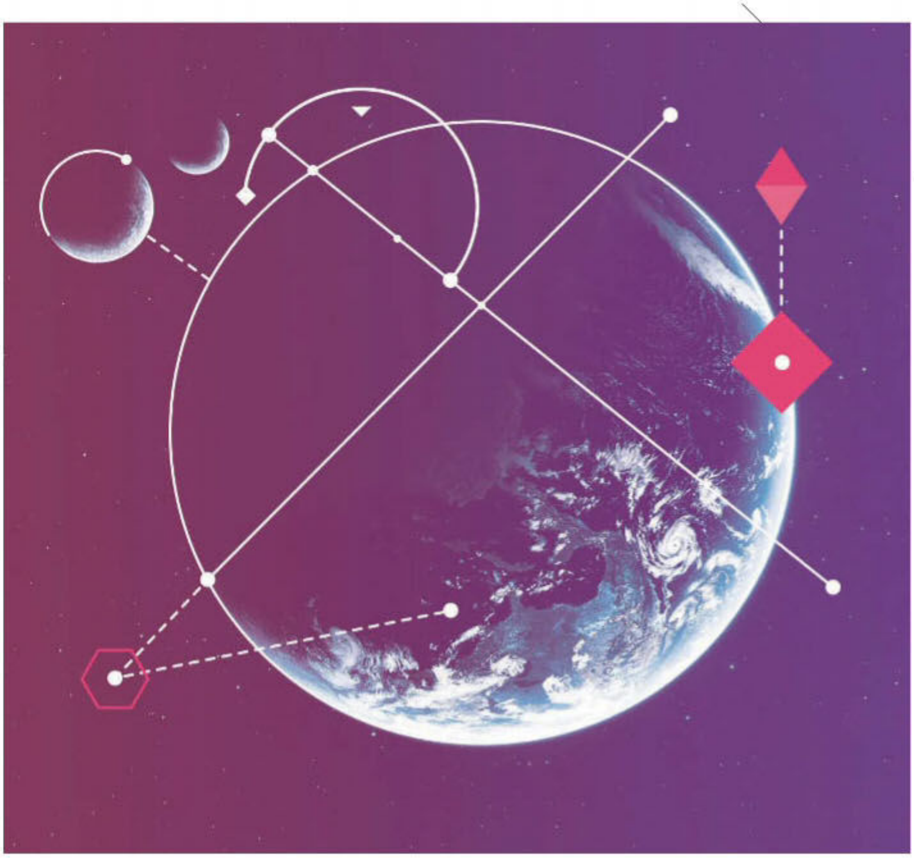
Any life that managed to survive on such a permalit planet, where seasons change in the span of days, would experience one of the weirdest night skies in the cosmos. Upon reaching one end of the corkscrew orbit and heading back towards the other star, the closest sun would seem to suddenly reverse its direction in the sky. "I hope the would-be inhabitants of the planet would be accustomed to this," says Oks, "and would not get scared each time it happened."

It's not yet evident how stars could force a corkscrew world to settle into such an unusual orbit, though snagging a passing starless "lone wolf" planet seems like their best bet. And while the transit method could spot these planets (see "Binary Worlds", page 85), their true screwball nature would be harder to identify.

According to Oks's paper, a better way to find corkscrew planets is via gravitational waves, the ripples in space-time predicted by Einstein's general theory of relativity. Corkscrew planets should generate telltale additional gravitational waves that would stand out against the background signals produced by interacting stars. Direct detection of gravitational waves from even the universe's densest objects has so far proved elusive, but with instruments getting ever more precise, Oks believes the distinctive behaviour of corkscrew planets could one day make them easily distinguishable. ■

Ideal homes

There's more than one way to make a planet fit for living, says Colin Stuart



LOGAN BRINKLEY

"EPPUR si muove" – "And yet it moves". Galileo's reported utterance following his trial for heresy in 1633 is perhaps science's most famous muttered riposte. Through the newly invented telescope Galileo had seen many things that couldn't be explained by the dominant cosmology of the time, rooted in the idea that all things revolved around Earth: things like moons crossing the face of Jupiter, or the changing phases of Venus as sunlight caught it at different angles – an impossibility if Venus's orbit encircled Earth. All this had made Galileo a champion of the Copernican revolution: the idea that all the planets, including Earth, orbit the sun.

Nearly four centuries on, we are on the cusp of another revolution in our cosmological understanding. From our vantage point on this orbiting world we have now spied almost 2000 others doing the same around far-flung stars (see "Worlds of pure imagination", page 84). A flood of information from planet-hunters such as NASA's Kepler space telescope, coupled with improved models of how planets and solar systems work, is forcing us to reconsider another set of geocentric views – this time about what a planet capable of harbouring life should look like. Increasingly it seems all our assumptions about Earth's "twin" are wrong. As the search continues, we may need to bear in mind that it will not look anything like Earth at all.

We take many things for granted when assessing a planet's suitability for life. First and foremost is the idea that, if biology elsewhere works anything like it does on Earth, life will be carbon-based – carbon chemistry has an unmatched complexity – and need liquid water as its essential solvent. That assumption leads directly to the concept of the habitable zone, first introduced in the 1950s. This is defined as the narrow region around a star where liquid water can exist. Too close to a star, and any water on a planet boils away; too far away, and it freezes. Only in the middling "Goldilocks zone" – neither too hot nor too cold, but just right – does life stand a chance of surviving.

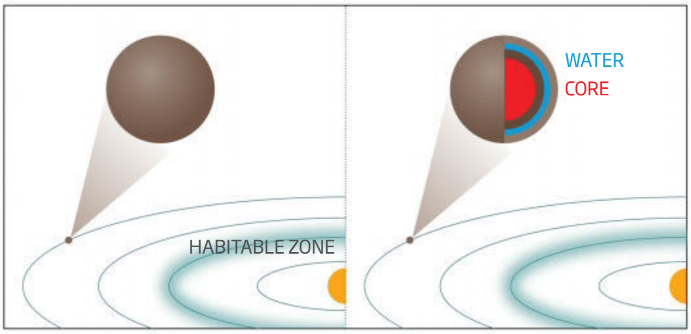
Our sun is well placed to host a planet that hosts life. Three-quarters of the stars in our Milky Way are fainter red dwarfs that pump out significantly less heat. The habitable zone of a red dwarf would be very close in, so close in that any planet orbiting within it would be "tidally locked": the gravitational grasp of the star would hold one side of the planet constantly facing towards it. That side would bake in perpetual daylight and searing temperatures, while the other would freeze ›

No place like home

Our ideas of where life can thrive depend on the idea of a "habitable zone" where liquid water can exist on an Earth-like planet. But that might not be the whole story

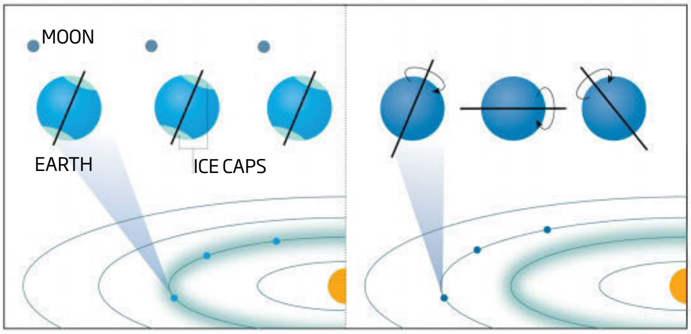
Life at depth

A rocky planet at Saturn's distance from the sun would be way outside such a star's habitable zone – but life might still exist in a subsurface ocean warmed by heat from the planet's core



Wobbly worlds

The tilt of Earth's axis is stabilised by our large moon – but a moonless, wobbling planet would develop no ice caps, and retain liquid-water temperatures beyond the habitable zone



KEPLER REVIVED

When NASA's Kepler space telescope was launched in 2009, it was equipped with four "reaction wheels", flywheels that rotated the craft and helped point the telescope accurately enough at stars to detect evidence of distant planets.

Three reaction wheels are needed for stable positioning, so when first one reaction wheel failed, followed by a second within twelve months, it seemed to mark the end of the mission. But an ingenious idea has prompted Kepler's Lazarus-like revival. The gentle nudging of radiation pressure from sunlight can act like a third wheel and stabilise the telescope. That allows Kepler to look for planets in one patch of sky for around 80 days at a time. After that time, Earth's passage around the sun means it has to be repositioned again to avoid being blinded by the sun's glare.

That's not enough time to spot Earth-like planets crossing the face of their stars if their orbits take a year. But if habitable planets really can hug in close to red dwarf stars (see main story), it would be more than enough to see them completing several orbits. The proposed pared-down mission, dubbed K2, has already proved it has what it takes, by independently spotting a planet already seen by another telescope.

in constant darkness – scarcely ideal conditions for the development of life. The closest thing we know in our solar system is Mercury. It is not quite tidally locked, but still experiences a temperature swing of 600 °C between the day and night side.

As it is, Earth is sufficiently far away to rotate stably on its axis, with the sun's heat distributed evenly to all sides of the planet. As Earth spins, it traces out a near perfectly circular orbit entirely within the Goldilocks zone – albeit, according to the latest research, rather more precariously close to its sultry inner edge than we had thought. Our unusually large moon is a further boon: its tug ensures that the tilt of Earth's axis – its obliquity – changes very little. All those factors add up to an invitingly constant environment in which life has thrived (see "Why are the sun and moon the same size in the sky?", page 9).

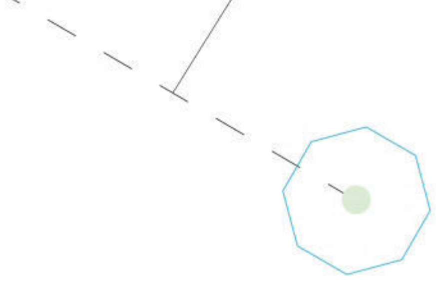
It also meant that when the Kepler telescope launched in March 2009, it had a goal: to track down Earth's doppelgänger. The telescope was named after the astronomer Johannes Kepler, who in 1619 first published the mathematical relationship between orbital distance and orbital time. That the mission was originally scheduled to run for three years is no coincidence. Earth takes a year to orbit the sun, so a similar planet in a similar position in a sunlike star's habitable zone will orbit in the same time. Three years is enough to spot such a planet crossing the face of its star three times, confirming its existence beyond reasonable doubt.

That is not what Kepler has seen. It did see a planet in the habitable zone, Kepler 22b, as far back as 2011, and Kepler 61b and Kepler 62e joined the club in 2013. But they are not at all like Earth – all three are significantly larger "super-Earths". Most models suggest that the stronger gravity at these planets' surfaces flattens them, making it easier for water to engulf their landscapes. Land warms up and cools down more readily than water, so Earth's exposed continents play a pivotal part in regulating our climate. "Ocean worlds may be more prone to climate instability and so be less habitable," says Lewis Dartnell, an astrobiologist at the University of Leicester, UK.

Eccentric worlds

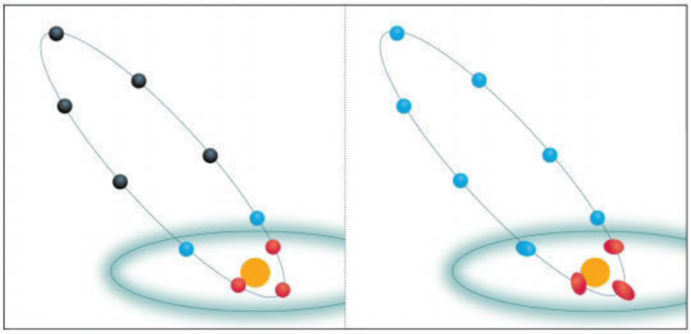
Geoffrey Marcy, formerly of the University of California, Berkeley, and his colleagues have also analysed changes in the host stars' light caused by the gravitational tug of their orbiting planets. Around three-quarters of Kepler's finds, although larger in size than Earth, are not massive enough to be watery, rocky worlds at all. Instead, they must be light planets rather like miniature Neptunes, their rocky cores surrounded by a puffed-up atmosphere containing large amounts of hydrogen and helium. "This opens up a concern that the predominant type of planet may not be suitable for biology," says Marcy.

Rather than finding other Earths, Kepler has in fact turned up all kinds of strange and unusual things. The Kepler 47 system, for instance, has two stars and at least three orbiting planets. There are also many



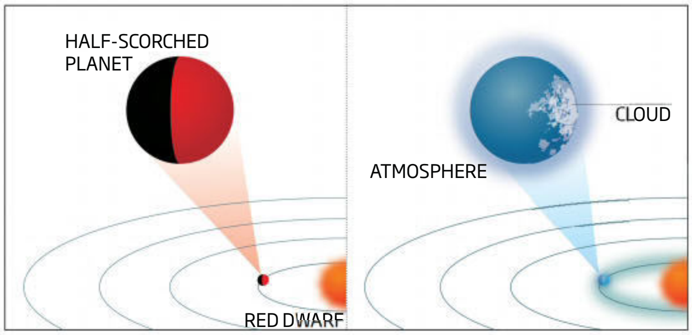
Central heating

Temperature swings on planets with elliptical orbits were thought to make them unsuitable for life – but when close to their star, gravitational distortions can store additional energy within them, warming them for the outer reaches



Homely dwarfs

A planet orbiting a faint red dwarf at liquid-water distance would have one face gravitationally "locked in" to the star. But cloud formation in an Earth-like atmosphere can help redistribute heat, perhaps making a habitable planet



instances of highly "eccentric" planets, with orbits that deviate significantly from the circular orbits typical of our solar system. Instead, the planets behave like comets, plunging into the warmer inner zone from the frostier outer climes. Perhaps the most unexpected find is Kepler 11 – a miniature version of our solar system, with five of its six planets huddling closer to their star than Mercury does to the sun. "It seems anything is possible within the rules of physics," says planetary scientist Sara Seager of the Massachusetts Institute of Technology.

Anything except, on the face of it, a planet with those qualities we believe provide a safe haven for life. But that's just where the facts are prodding us towards a rethink. "We might have been making a similar mistake to the pre-Copernican era, of thinking that we're special and that all habitable planets must share the same attributes as Earth," says Marcy.

Oddly, some of the motivation for a change of heart comes from closer studies of life on our own planet. Over the past few years we have discovered organisms eking out an existence in Earth's depths – most startlingly, nematode worms 3.6 kilometres down at the bottom of South Africa's deepest gold mine. Because only a fraction of possible subsurface habitats have been studied, Dartnell is one researcher reaching a conclusion alien to our conceptions even of a few years ago. "Life in the deep biosphere on Earth grossly outnumbers the ecosystems that we're familiar with on the surface," he says.

That has consequences for life elsewhere. "Many more planets can be considered habitable once the subsurface is taken into account," says Sean McMahon, now at Yale University. In September 2013, McMahon and two colleagues published a paper examining the potential for life in underground water kept liquid by heat emanating from a planet's core. The deeper the water lies, the better shielded it is from the outside temperature, so the further the planet can be away from its star while remaining habitable. Life 5 kilometres down could survive on a planet with an orbit

> "We are making the mistake of thinking all habitable planets must look like Earth"

at three times the radius of the traditional habitable zone. If life were sunk as low as 10 kilometres, the habitable zone would rocket out past the orbit of Saturn – 14 times the accepted distance around a sunlike star (see graphic).

Similar considerations mean we can't rule out subsurface life in the outer reaches of our solar system. The tidal friction generated on Jupiter's moon Europa as it orbits its massive host may have melted water beneath its crust, perhaps creating a subsurface ocean with the conditions necessary for life to get started (see "Living snowballs", page 42).

In January 2014, at a meeting of the American Astronomical Society in Washington DC, John Armstrong of Weber State University in Ogden, Utah, highlighted another scenario with the potential to shift the habitable zone. Earth's moon-stabilised tilt might be a boon, but a changing tilt need not be a disadvantage: it just changes the rules of the game. "Obliquity variations can suppress the build-up of polar ice sheets, meaning less heat is reflected away into space," he says. According to his models, a wobbling planet might be able to retain liquid water at almost twice the distance from its star as an Earth-like non-wobbler.

Future missions might glimpse this changing obliquity by looking for variations in a planet's brightness as light bounces off wobbling polar caps. Not that such a planet would necessarily harbour Earth-like life, however – at least not visibly. "It's unclear how complex ecosystems of multicellular

animals and plants would cope with the wildly swinging climate of a wobbling world," says Dartnell. "But for bacteria below the surface it probably makes no difference at all."

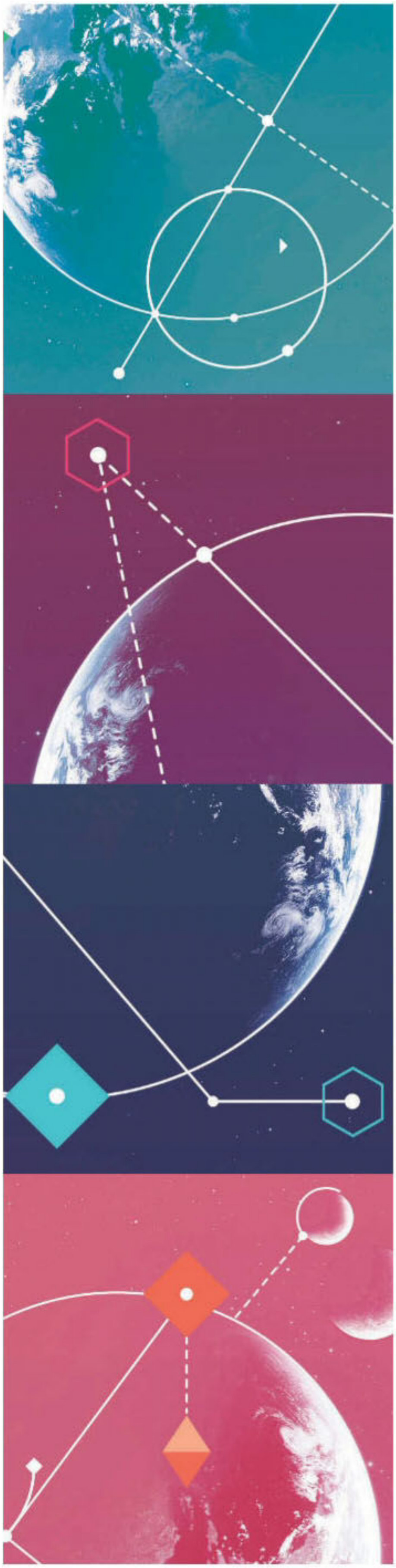
It would be significant if habitable zones can extend out further from their stars, not least because fainter stars such as red dwarfs would be back in the game: life-bearing planets could orbit at distances large enough to keep them from being tidally locked. But even tidal locking might not be so much of problem, according to more advanced climate models developed over the past decade. They show that if a tidally locked planet were to have the same sort of nitrogen-rich atmosphere as Earth, heat could be efficiently transported to the perpetually dark night side, creating a more balanced, balmier climate.

Close to home

The potential for red-dwarf habitability was underscored two years ago by the first 3D atmospheric model of a tidally locked planet, created by Dorian Abbot of the University of Chicago and a couple of colleagues. It threw up a tantalising possibility: that clouds form more readily directly under the unmoving spotlight of the star's glare.

Clouds reflect more radiation back into space, meaning a cloudy planet can get even closer to its star while maintaining a reasonable temperature – extending the habitable zone inwards this time. "This doubles the number of possible habitable planets around red dwarfs," Abbot says. Given the preponderance of red dwarfs in our galaxy, that is a huge

"The number of red dwarfs in our galaxy makes the findings a huge boost for life"



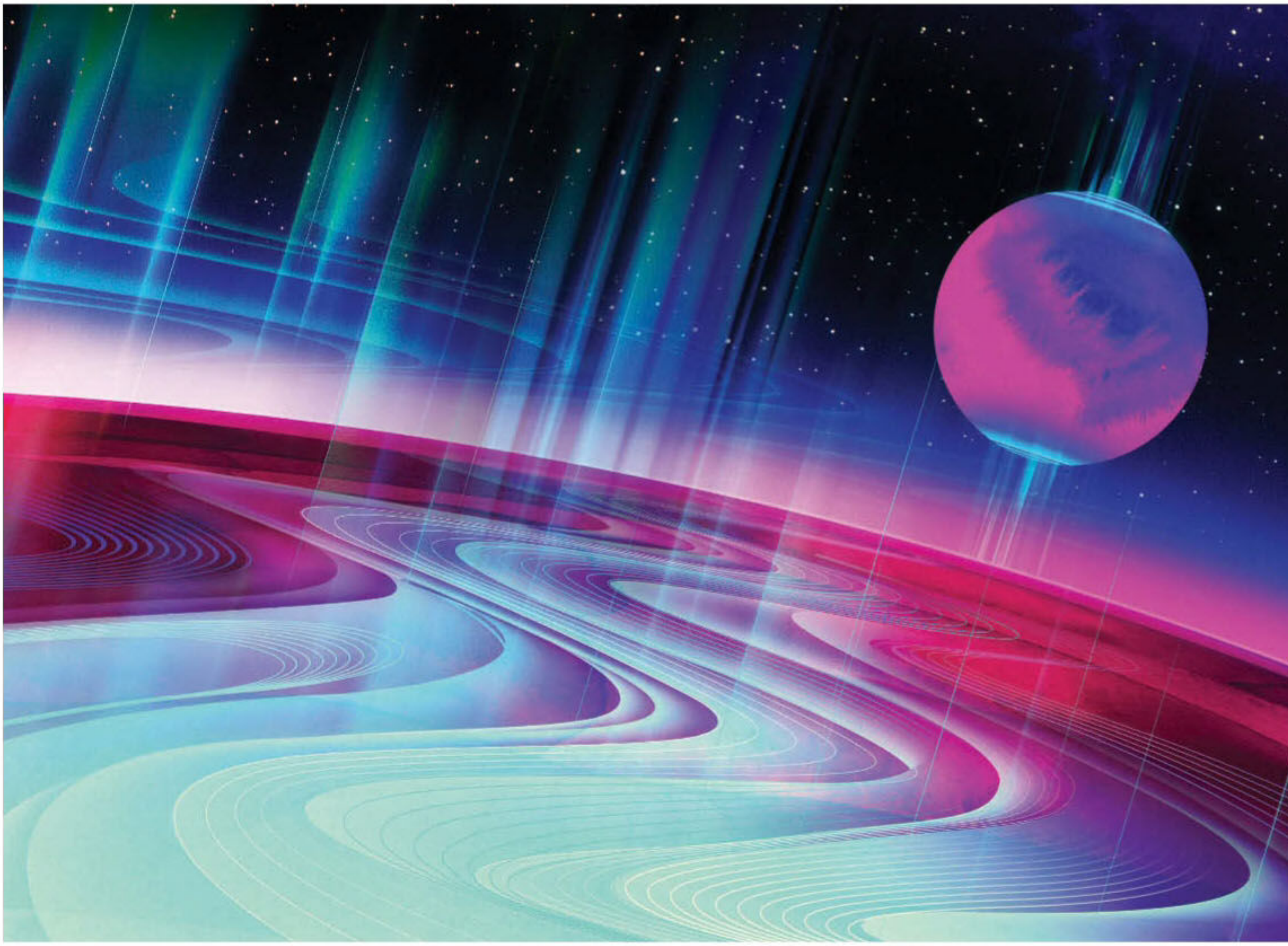
boost to the number of potentially habitable planets, and for our chances of finding them (see "Kepler revived", page 90).

In fact, habitable zones around some stars might be rather movable feasts. Modelling by Greg Laughlin, an astronomer at the University of California at Santa Cruz, indicates that liquid water, and hence life, might even survive on a planet on a highly elliptical, comet-like orbit. During its closest approach to a star, the heating rate on such a world would go up 20 times in a matter of hours – but the planet might "take the insult", says Laughlin. Although the temperature at the equator would reach that of an oven, heat would be dissipated quickly enough at higher latitudes for any existing water to remain in its liquid form rather than boiling off. Meanwhile the extreme tidal forces inflicted by the star during the period of closest approach would inject gravitational energy into the planet's core, providing it with a source of warmth even during its icy passage further from the star.

Whether such a world could host multicellular creatures is still debatable: again, it is hard to know how photosynthetic life would cope with such wildly changing amounts of sunlight. "It would be very different from the Earth, but we need to keep an open mind," says Dartnell. At least such planets are easier to spot: they get much closer to their stars, making for a more noticeable dip in brightness as they transit across its face. "The probability of detecting these worlds can go up by a factor of ten," says Laughlin.

One by one, then, all the "rules" we have established that say life-harbouring planets must look and act like Earth seem to be falling away. Armstrong goes a step further, and says unearthly planets might even be more conducive to life than our home. Along with René Heller, formerly at McMaster University in Hamilton, Ontario, Canada, he has set out the characteristics of "superhabitable" worlds, concluding that a planet more massive than Earth orbiting a star smaller than the sun would boast advantages such as slower tectonic activity and reduced exposure to high-energy stellar radiation.

That might be a blow to our earthly self-esteem. But just as centuries ago we discarded Earth from the centre of the universe, now might just be the time to dispense with our planet as the poster child for habitability. In the search for life elsewhere we need to keep an open mind, says Seager. "If we limit ourselves to just Earth's twin, then we are dead in the water." ■


SAM CHIVERS

Good to glow

The spectacular light shows in our polar skies don't just happen on Earth. Glimpses of the auroras on other planets could reveal a world of information, finds Sophie Hebden

HIGH in the sky, giant ribbons of colour dance and flicker. It is a good night for aurora watchers. The strips of red turn cyan and back again as the clouds roll by. Stars twinkle in the night sky beyond. A full moon is rising above the horizon, while the crescents of another two moons arch majestically.

Welcome to one of the many planets outside our solar system. Nearly 2000 have been found so far, most by watching for wobbles in starlight or a brief dimming of their parent star. Such techniques can tell us about a planet's mass, radius and orbit. Other details can be gleaned from the handful of planets that are big enough and close enough for molecules in their atmospheres to be detected.

Now space scientists think that alien auroras could further enhance our understanding of exoplanets. No one has ever seen the auroral light from an exoplanet – even from those orbiting the nearest of the stars outside our solar system. The light is simply too faint to travel the huge distances involved. But auroras have another trait that researchers think could be detected: they emit radio waves.

Detecting such radio emissions from just one exoplanet would give us a wealth of information that is not available from other techniques. As well as revealing previously hidden worlds, different aspects of the emission could also allow us to calculate the length of an exoplanet's day and the strength of its magnetic field. It could even provide clues about the internal processes that drive the magnetic field, as well as how the planet interacts with its parent star and, possibly, whether it has any moons. "All of this is about understanding more about exoplanets than what we can determine from present methods," says Jonathan Nichols of the University of Leicester in the UK.

Here on Earth, the northern and southern lights are the result of electrons accelerated by the solar wind colliding with gas molecules in the upper atmosphere, causing them to radiate light at a characteristic wavelength. Oxygen emits the most familiar greenish-yellow light, and nitrogen molecules glow red or blue. But before they collide, the electrons gyrate around the planet's magnetic field lines and in the process emit radio waves.

The sky-lighting effect isn't just confined to Earth. Auroras have been spotted on Jupiter, Saturn, Uranus and Neptune, and last year a brown dwarf star became the first object outside our solar system to exhibit the phenomenon. And there are good reasons to expect that at least some exoplanets will have them too, based on a few detections of solar-like flares thought to be caused by the magnetic field of the host star getting entangled with the magnetic field of a planetary companion.

"There are good reasons to expect that at least some exoplanets will have auroras like Earth's"

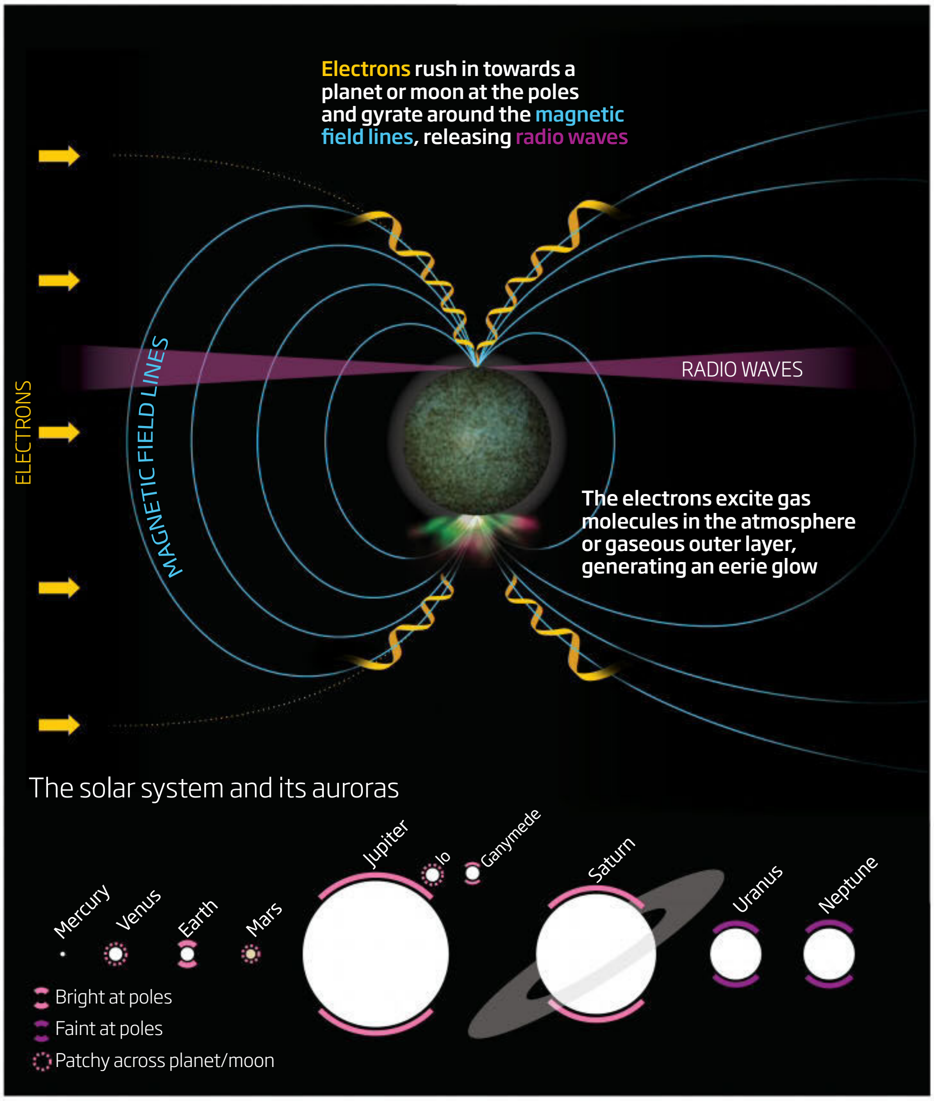
Of all the auroras in our solar system, Jupiter has the brightest. Twice as massive as all the other planets combined, Jupiter is the king of the planets. It also has the strongest magnetic field and the most beautiful rings of auroras at its poles. We can't observe them using ground-based telescopes because the light from Jovian auroras is mostly ultraviolet, which cannot penetrate Earth's atmosphere.

The first photographs were beamed back by NASA's Voyager 1 spacecraft when it flew by the planet in 1979. Today we rely on ultraviolet images from the Hubble Space Telescope and X-ray images from the Chandra Observatory as they orbit Earth.

But it was, in fact, low frequency radio signals from Jupiter that first revealed that it has auroras. The signals allowed scientists to calculate the planet's magnetic field strength long before we sent Voyager 1 there for a

Guiding light

Auroras at Jupiter's poles were first spotted from the radio waves they produce, not the more familiar light shows we see on Earth. Such radio waves could be used to find planets outside our solar system



direct measurement.

Radio is still a promising means of finding and studying exoplanets, because if a planet has a magnetic field, it is potentially capable of emitting radio signals that are stronger than those of its parent star.

"If you want to observe a planet far away and you are looking in optical or infrared wavelengths, the planet is much fainter than its parent star, so it's very difficult to detect," says Philippe Zarka of the Paris Observatory in France. The reason is that stars are very hot and bright at optical wavelengths and planets are not, so our view of them is swamped by starlight. "By contrast, the radio emission is related to the magnetic field strength of the planet and the electrons moving along it, not its temperature," he adds.

To be able to predict and interpret these observations, however, our understanding of Jupiter is crucial. "A lot of the exoplanets found so far resemble Jupiter in some respects," says Nichols. "Jupiter provides a link to other bodies that we can't get to."

Nichols is a dedicated Jupiter enthusiast, having focused on the planet and its auroras for his PhD and stayed with it ever since, alongside study of the auroras on Saturn. "Jupiter is a fascinating system, it's hard not to evangelise. My wife just rolls her eyes these days," he says.

In the low frequency range, at a few tens of megahertz, Jupiter's radio emissions show up as brightly as those of our sun, but even this would not be detectable if Jupiter were as far away as the nearest stars. Not all is lost, though. "We expect that some planets will produce radio emissions much stronger than Jupiter," says Zarka, who is simulating how an exoplanet could emit a sizable radio signal, and what that signal could reveal.

For example, the frequency with which an aurora emits radio waves is thought to be dependent on the strength of the magnetic field. Helpfully, this radio emission is beamed outwards from the magnetic field in conical beams, which sweep around as the planet rotates, like a lighthouse. This sweep would appear as a pulse of radio waves at a telescope on Earth, allowing us to calculate the planet's rotation period.

The signal is also circularly polarised, meaning that its electric field rotates as the signal travels. This allows us to differentiate between planetary signals and radiation from the star, which is unpolarised because it is produced by bursts of electrons rushing through its outer atmosphere. "If you measure strong circular or elliptical polarisation, it's very likely to have come from the planet rather than the star," says Zarka.

Tune in to other worlds

The first group to search for exoplanets using radio was led by William Erickson, professor emeritus at the University of Maryland. Inspired by the success of Jupiter's auroral radio signals, in 1977 his team looked for planets around nearby stars by searching for pulsed radio emissions from alien auroras. Using the Clark Lake Radio Observatory near Borrego Springs, California, the group looked at 22 stars, estimating that their telescope could detect a burst if it were 1000 times stronger than Jupiter's strongest bursts. Nothing came of it. Radio telescopes at the time were not sensitive enough to pick up signals from such distant sources.

Now, 38 years on, interest in auroral radio emissions has been reignited by the completion of a new, highly sensitive radio telescope called the Low Frequency Array. LOFAR is the largest and most sensitive radio telescope below 250 megahertz ever constructed.

Ten years in the making, it is a vast array of over 45,000 small antennas, with its heart in the Netherlands – an army of tethered poles rising above a grassland nature reserve in the quiet north east of the country. Other antennas are installed across France, Germany, Sweden and the UK. Scientific operations began in 2012 and Nichols hopes to uncover exoplanets in the very near future.

In the meantime, his team and Zarka's have been calculating what sort of giant planets could emit radio signals detectable by LOFAR, and what the signals could reveal about the underlying planet. This is where expert knowledge of auroral processes in our own

backyard comes into its own.

Both teams have considered a Jupiter-like planet, because most exoplanets found so far have a mass greater than or equal to Jupiter. There are two possible scenarios for strong radio emissions.

First, the planet orbits close to its parent star and is strongly buffeted by the solar wind, which reconfigures the planet's magnetic field. This drives flows of charged particles and aurora-producing currents, characteristic of auroral processes on Earth.

Zarka and Sebastien Hess, then based at the Atmosphere, Environment and Space Observation Laboratory (LATMOS) in Guyancourt near Paris, France, considered this "hot Jupiter" scenario, developing a model to predict the radio signals that could arise depending on how the planet interacts with its parent star and where the auroral emission occurs on the planet.

"We found the model very successful at accounting for the radio emissions from planets in our own solar system," says Zarka. What's more, they found that they could analyse a radio signal from an exoplanet and use it to deduce physical quantities that cannot be found any other way. These include the inclination of a planet's orbital plane, the tilt of the magnetic field relative to the rotation axis, as well as rotation period, orbital period and magnetic field strength. This will help us to understand the evolution of exoplanets as well as the way they behave today.

The second option is that the radio emissions are mainly associated with an orbiting moon, as is the case for Jupiter. Its third largest moon Io is a volcanic world, with eruptions spewing ionised gas towards Jupiter at a rate of 1000 kilograms per second. Unlike the northern and southern lights on Earth, which are due to the solar wind, it is this ionised gas that is mostly responsible for Jupiter's auroras. "It is reasonable to assume that such active moons may be relatively prevalent amongst Jupiter-like exoplanets," says Nichols.

Nichols tackled this second scenario, examining how a planet's rotation rate, rate of outflow of ionised gas from a moon, orbital distance and the ultraviolet brightness of its parent star would affect radio emissions. He found that massive, fast-rotating planets could produce bright radio emissions detectable from 150 light-years away.

So far there are no confirmed detections of auroral signals from exoplanets in the ongoing searches at other telescopes. Walid Majid of NASA's Jet Propulsion Laboratory in

NASA/CXC/SAO

Jupiter has the brightest auroras in the solar system

Pasadena, California, and colleagues have looked at a small number of exoplanets using the Giant Metrewave Radio Telescope (GMRT) located 80 kilometres north of Pune in India. They believe the main reason for not detecting any radio signals from these planets is that the instrument can't observe at a low enough frequency.

For example, Jupiter doesn't emit intense radio waves above 40 megahertz, a cut-off frequency that depends on the planet's magnetic field strength. So if you don't look below this cut-off frequency for an exoplanet, you wouldn't see anything. The lowest frequency GMRT can detect is 50 megahertz.

LOFAR will be able to detect radio signals down to 10 megahertz, which is more promising. However Earth's atmosphere blocks frequencies below 10 megahertz, so you would need a space-based antenna to search below this limit. Majid suggests the surface of the moon would be a good location for such a telescope.

"The existence of a magnetic field is favourable for the habitability of a planet or moon"

Telescope sensitivity also influences our ability to observe auroral radio signals. This can be improved by adding more antennas or by identifying and removing noise in the signal caused by other sources of radio waves. Majid is optimistic that radio astronomers are up to the task, with LOFAR underway and another huge radio telescope called the Square Kilometre Array, which is under construction in South Africa and Australia.

"If we don't detect anything with LOFAR after a few years, it won't be because we are missing the beams of radio waves from exoplanets," says Zarka. "It will be because there is no emission. I have a fair hope that we will detect something. But of course, this is research, so you're never sure."

Space physicists hail low frequency radio as "a science frontier for the next decade". Certainly as the sensitivity of LOFAR increases, and our detection of exoplanets using other techniques improves, being able to define the magnetic field characteristics of a planet will reveal more and more. "The existence of a magnetic field is interesting as we try to understand planetary evolution, but also because it has effects that are favourable for the habitability of a planet," says Zarka. Earth's magnetic field produces a large protective shield called the magnetosphere that deflects energetic charged particles, such as cosmic rays that can damage DNA and potentially prevent life from evolving. It also preserves our atmosphere by trapping the ionised upper layers of the atmosphere.

The importance of such a magnetosphere for the habitability of a planet is partly what has motivated the European Space Agency's mission to Jupiter and its moons in 2022 – dubbed the Jupiter Icy Moons Explorer, or JUICE – which will eventually go into orbit around Jupiter's largest moon Ganymede.

Ganymede is made of rock and ice and has its own magnetic field and auroras. "It's one of the best places in the solar system to look for extraterrestrial life," says Nichols. He's excited by the prospect of sending a spacecraft directly to the action, something you could never do for exoplanets. For this reason, and because Jupiter has already revealed so many interesting features, "Jupiter will always be my favourite planet", says Nichols. ■

Home, sweet exomoon

Forget planets – there's a new place to look for life out there, says Andy Ridgway

THE diminutive sun set hours ago, but a giant orb suspended in the sky still suffuses the scene with a low, orange-red reflected glow. The air is thick with volcanic soot, yet surprising activity is discernible through the fog. Large-eyed predators roam the landscape, padding through black, wide-leaved foliage.

A weak sunrise inches over the horizon, as yet another seismic rumble ripples through the surface. A faint new day will soon dawn on this moon of a gas-giant planet, orbiting a red dwarf star thousands of light years from Earth.

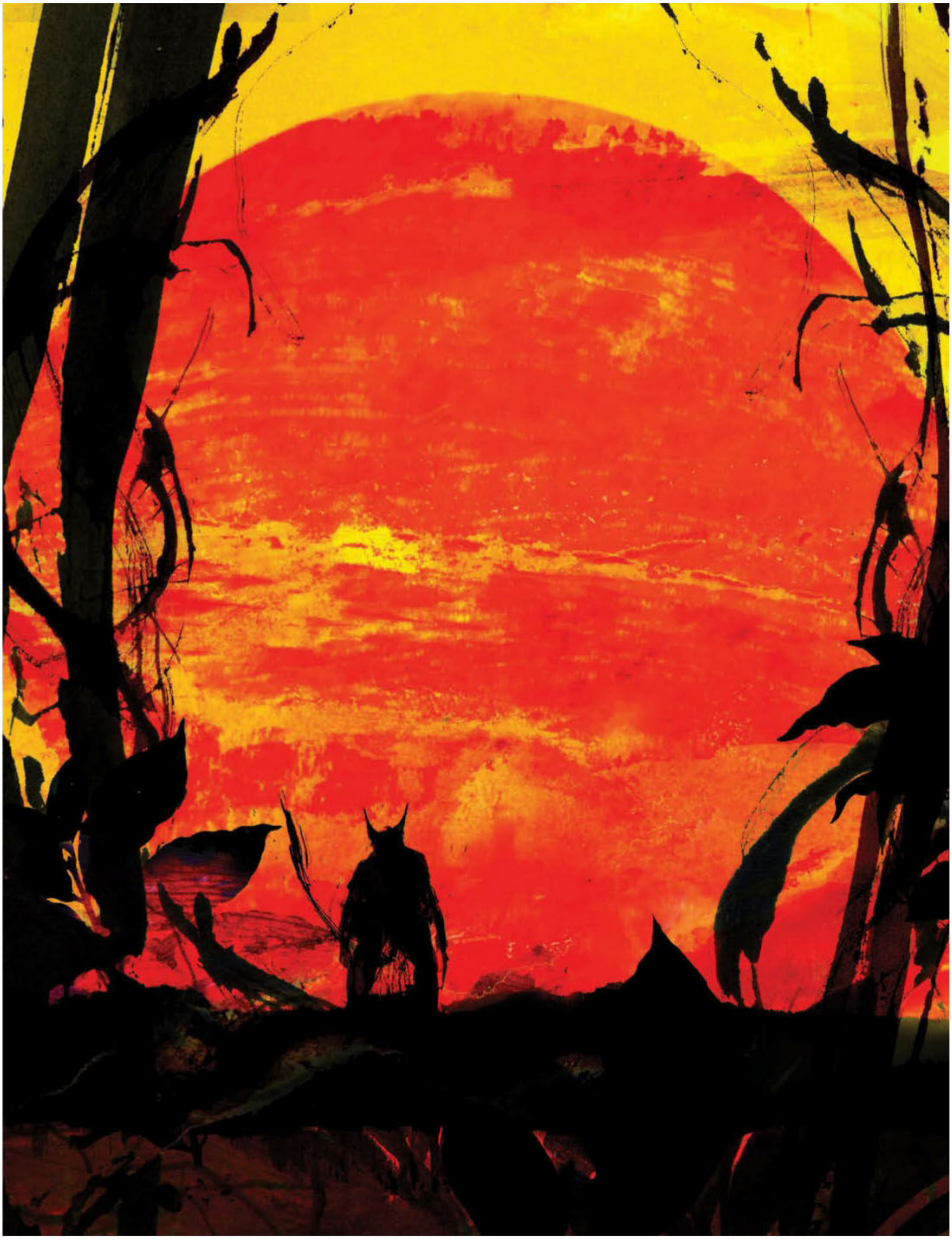
Lunar life is a staple of science fiction. Lush imagined moons such as Endor, forested home of the Ewoks in *Star Wars*, or the magical Pandora of *Avatar* readily capture our imaginations. Perhaps that's because they represent something familiar in many ways, but altogether different.

An Endor or Pandora is possibly too much to ask for, but something like the gloomy, volcanic moon orbiting a gas giant might not be too wide of the mark. And as we learn more about planetary systems – in our solar system and elsewhere – there's a growing feeling that, in the search for alien life, we are better off looking not at planets, but at moons. And although no "exomoon" in another solar system has been discovered quite yet, we could be just the blink of a telescope away.

The possibility of discovering alien life is one big reason why the discovery of exoplanets orbiting other stars has generated so much excitement over the past two decades. Instruments such as NASA's Kepler space telescope, the most prolific of planet hunters, have been providing us with an almost constant stream of other worlds, with the confirmed total now pushing 2000.

The search continues for Earth's twin – or at least, any form of habitable planet. There have been some close calls, but in many ways exomoons are more promising. Partly that's a pure numbers game. Our solar system has only eight major planets (and only one habitable one), but between them they have 168 known moons. If our backyard is anything to go by, there are likely to be far more moons than planets out there.

The crucial hunting ground for life has conventionally been a star's so-called habitable zone – the thin girdle around it where water, life's solvent, can exist in liquid form. Kepler has shown us that the most abundant planets orbiting here aren't small, life-friendly rocks like Earth, but gas giants the size of Jupiter or bigger. It's hard to conceive of such planets harbouring life, but easy to think they might have rocky moons that can. "Moons might even outnumber terrestrial planets here and therefore be the most abundant type of inhabited world in the universe," says



SIMON PEMBERTON

ENDOMOONS

While excitement grows about the chances of finding life on "exomoons" in other solar systems (see main story), we haven't yet exhausted the possibilities offered by the icy moons of our own outer solar system: the endomoons.

ENCELADUS: Saturn
Radius: 252 km
Average distance from sun: 1.4 billion km
Environment for life: A hidden ocean of salty water perhaps the size of Lake Superior, most obviously apparent through geysers shooting through the moon's icy surface near its south pole. Early last year NASA's Cassini probe found evidence the ocean might be warmed and supplied with minerals through undersea hydrothermal vents.
Possible life: Anything near these vents may resemble microbial life that lurks near Earth's deep-sea vents – a possible cradle for life here.

EUROPA: Jupiter
Radius: 1561 km
Average distance from sun: 780 million km
Environment for life: Ridges criss-crossing Europa's surface might be generated by tidal forces warming a voluminous subsurface ocean that has probably been around for 4 billion years.
Possible life: One of the closest analogues for Europa's ocean is the subglacial Lake Whillans in western Antarctica, home to nearly 4000 species of microbe. But Europa's waters are likely to be alkaline and salty, chemically more akin to soda lakes in eastern Africa – so any microbes there are likely to be unique.

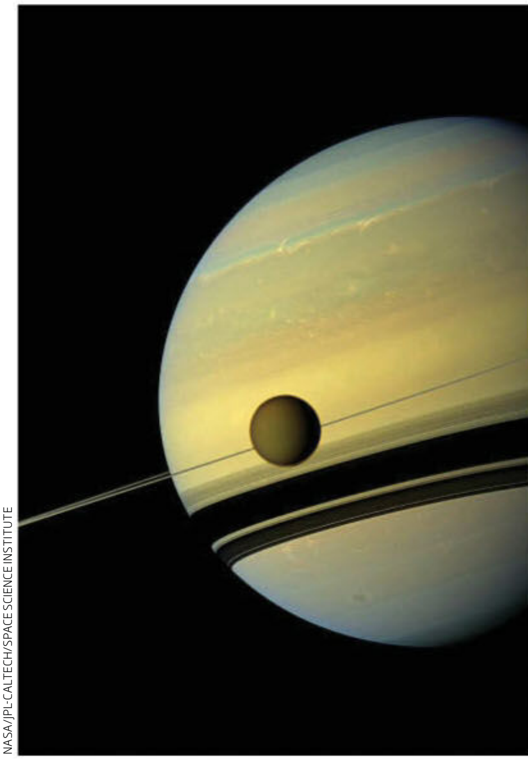
GANYMEDE: Jupiter
Radius: 2634 km
Average distance from sun: 780 million km
Environment for life: In March 2015, the Hubble Space Telescope showed that a vast ocean of salty water – amounting to perhaps more than all of Earth's surface water – exists beneath the icy surface of the solar system's largest moon.
Possible life: Microbial ocean-dwelling lifeforms.

TITAN: Saturn
Radius: 2576 km
Average distance from sun: 1.4 billion km
Environment for life: Titan's frigid surface has seas of liquid methane. Its atmosphere is rich in organic compounds formed when sunlight breaks down methane – but could some form of life also be generating fresh methane here?
Possible life: A recent study suggests cells on Titan would have methane-based membranes, rather than the lipid bilayers of our cells.

exomoon hunter René Heller of the University of Göttingen in Germany. So the search is on – with the added inducement of having your name associated with that first discovery. "You really want to find an exomoon rather than planet number 4350," says Heller.

But while there has been the odd unconfirmed candidate in recent years, there has been no definite exomoon sighting yet. "It's mostly because they are probably very small," says David Kipping of Columbia University in New York City.

Kepler, for example, finds exoplanets by looking for the dip in a star's brightness caused by an orbiting body transiting across its face. The size of this dip diminishes with the circumference of the transiting body, so something half the size will be four times harder to see. Kepler was designed to find Earth-sized planets; the largest moons in our solar system, Jupiter's Ganymede and Saturn's Titan (see "Splash of the Titans", page 47), each have a radius about 40 per cent of Earth's. If that size is typical, exomoons are right at the limits of existing telescopes.



NASA/JPL-CALTECH/SPACE SCIENCE INSTITUTE

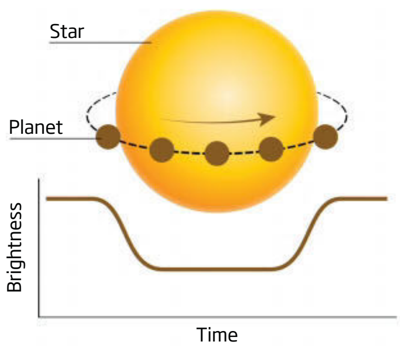
But it's not just size. Planets sail across their star at nicely regular intervals, but a moon can be behind its planet, in front of it, or at some point to the side, making any additional small dimming effect appear irregularly (see "Moon spotting", below). "It could happen a few hours before or after the transit, and sometimes early and sometimes late," says Kipping.

Nevertheless, exomoon hunters are growing in confidence. "I think David Kipping and I would agree that maybe we are at the stage that the exoplanet hunts were at in the late 80s and early 90s," says Heller. "The techniques are there, so we now have to search for these moons."

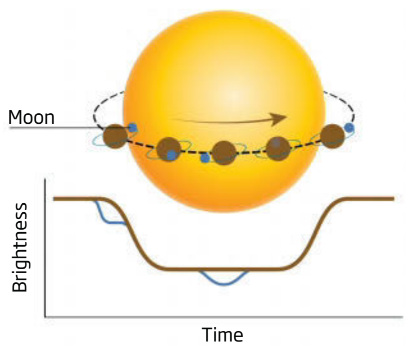
Kipping's Hunt for Exomoons with Kepler project is perhaps the furthest advanced. His team starts with Kepler information on known planets and painstakingly develops predictions for a range of effects such as when a possible moon would transit and how its gravity might affect the planet's speed at certain points, changing the duration of its transits. They then search for hints of such things in the data. "Each of these effects may only just be detectable by themselves," says Kipping. But see several of them with the same

Moon spotting

The signature of a moon orbiting a planet in another solar system is difficult to see

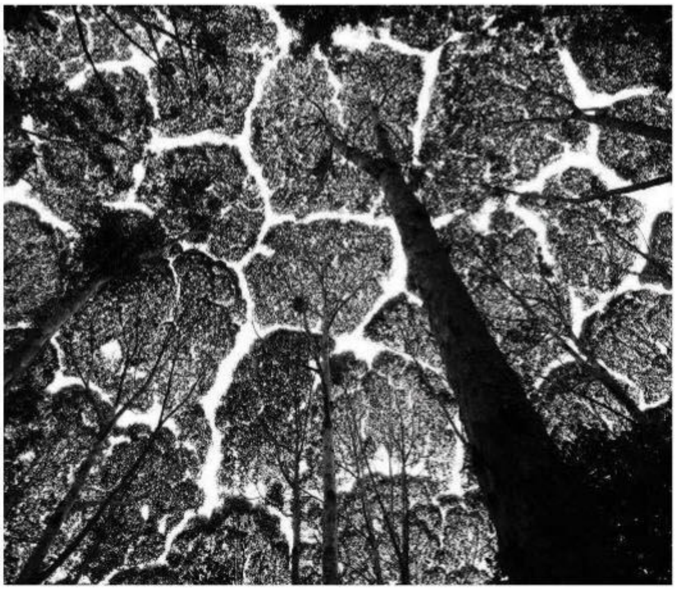


A planet causes a regular dip in the light reaching us from a star, so it is fairly easy to detect



A moon orbiting that planet will cause additional small dimmings - but at widely varying times depending on where it is in its orbit

Saturn's moon Titan might harbour exotic microbial life



STUART FRANKLIN / MAGNUM

planet, and you might be on to something.

With the help of NASA's Pleiades supercomputer, Kipping hopes to analyse over 300 planetary systems. Their technique should be sensitive enough to discover the smallest exomoons capable of sustaining an Earth-like atmosphere in at least 1 in 4 of the systems the team surveys, if they exist. “In terms of moons that could have life on them, and by that I mean Earth-like life, we are already definitively sensitive,” Kipping says. “When we've finished this survey, I will be able to tell you how often Pandora actually exists.”

Heller's own modelling, meanwhile, suggests a planet several times the size of Jupiter could have a moon the size of Mars – and that should be big enough for Kepler to spot. His team has developed a technique that involves comparing multiple transits of the same planet and looking for any variations in light that might indicate the presence of a third bod He is currently applying for funding to use the approach on Kepler data.

Last June, meanwhile, Joaquin Noyola of the University of Texas at Arlington started listening for exomoons. That might sound unfeasible, but Jupiter's moon Io is known to trigger radio emissions as it moves through the planet's magnetic field, and Noyola hopes exomoons will do the same. A moon-induced radio signal would be very weak by the time it reaches Earth, so Noyola is testing the idea by listening in to Epsilon Eridani b, which at 10 light years away is one of the closest known exoplanets. Just on the off chance, he is also eavesdropping on two other nearby star systems not yet known to contain exoplanets.

One way or another, the moon hunters are closing in . “My gut feeling is that we'll find an exomoon in the next few years,” says Heller.

“Exomoons can remain habitable far further out from their stars”

That's when the hard work will begin. To answer that all-important question about life, we need to know what the exomoons are like – do they have liquid water, or an atmosphere containing suggestive gases such as oxygen?

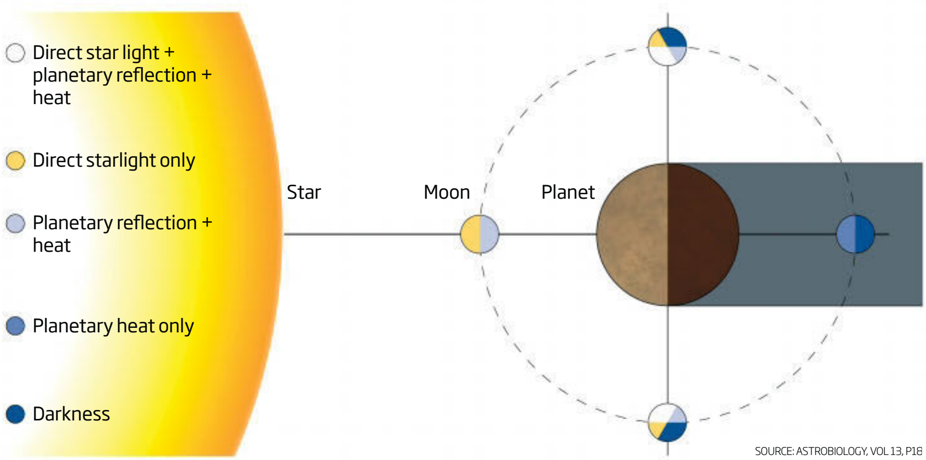
With exoplanets, that has proved tricky. The best way to sniff a distant planet's atmosphere is to look at the spectrum of starlight reflected from its surface, which will look different depending on what atmospheric gases are present to absorb various wavelengths. But for an exoplanet to be toasty enough to retain liquid water, it must be relatively close to its star (see “Ideal homes”, page 89), and that generally means the delicate signal of light reflected from the planet gets drowned out by the star itself.

Not so with exomoons, says Edwin Turner at Princeton University – for the simple reason that they can remain habitable further out. There has been a lot of talk in recent years about moons surrounding the gas giants in the outer reaches of our own solar system, such as Europa or Enceladus, being potential homes to life – albeit only primitive microbial life (see “Endomoons”, far left). These bodies lie way outside our star's traditionally defined habitable zone, but in the neighbourhood of a giant planet additional sources of energy become available – light reflected from the planet, for example, as well as heat radiated as a young planet takes in gas and shrinks.

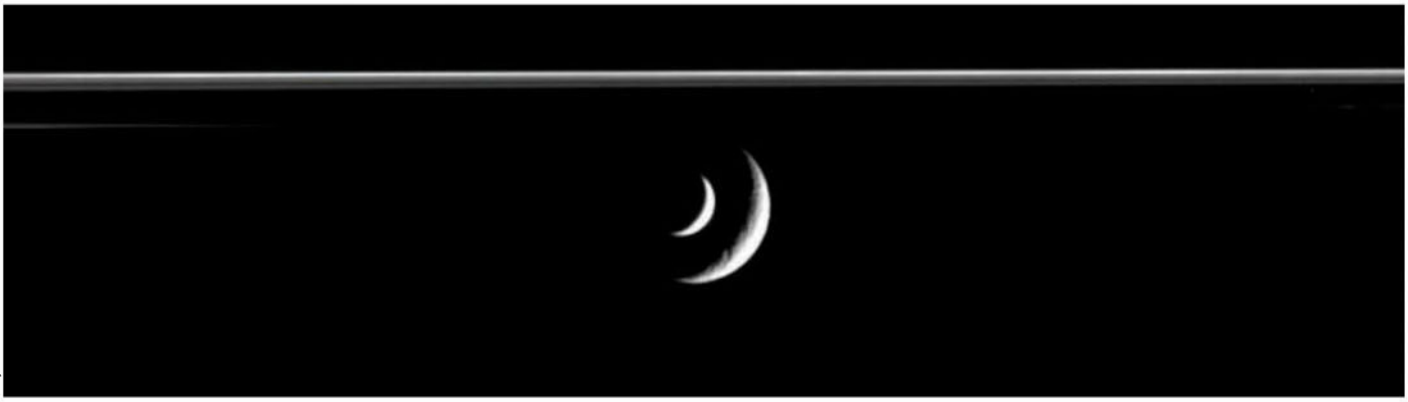
Then there is the effect known as tidal heating. In a system with more than one moon, varying gravitational pulls as the bodies orbit the central planet can stretch and squeeze a moon's interior, causing friction that can generate enormous internal heat. (Our moon's smaller pull doesn't generate much heat, but does create ocean tides.) Such effects could extend the region around a star in which liquid water can exist well beyond the habitable zone towards a “habitable

By the light of an evening planet

Life on a moon would experience direct sunlight plus light reflected from its planet and heat emissions too – making for up to four phases of day and night



SOURCE: ASTROBIOLOGY, VOL 13, P18



SSI/JPL/NASA

edge" much further out.

It's a fine balance – and any life on such a moon would have had to evolve in conditions of low light and high seismic activity (see "Plants of Pandora", below). Then there are the strange phases of day and night that a body illuminated both directly by a star and indirectly by a planet would experience (see "By the light of an evening planet", page 101).

Nevertheless, recent work by Turner and Vera Dobos, now at Konkoly Observatory in Hungary, shows how natural feedbacks could act as a thermostat on tidally heated moons, increasing the likelihood that they will have surface water. For example, if an ice-covered moon is close to its neighbouring planet, strong tidal forces might melt its ice, but the resulting water and slush would deform more easily and so generate less heat. That would prevent the world steadily getting hotter and burning off the water. The opposite effect would tend to keep ice – or indeed any surface material – near its melting temperature on moons further out from their planet. "This is an indication of why there might be a lot of liquid water in tidally heated moon systems," says Turner.

"A large, heated moon far enough from its star might even be visible directly"

A large, heated moon far enough away from its star's glare might even be visible directly without any sophisticated detection algorithm. "You would point your telescope at it and take a picture of it at infrared wavelengths," says Turner. "It's plain old straightforward astronomy."

Even so, that would be right at the limit of existing infrared telescopes. The Spitzer Space Telescope would only see a nearby exomoon that's brutally hot – around 700 °C, in fact. But NASA's James Webb Space Telescope, due for launch in 2018, should be able to detect one at a relatively cool 27 °C and much further away from Earth.

There's even a chance the right infrared telescope might see signatures of atmospheric gases such as carbon dioxide and methane directly imprinted in the glow of a tidally heated planet, without being overwhelmed by light from the star. The fact the infrared light would be radiated from the surface of the moon, rather than being reflected starlight, changes the interpretation of what we see somewhat, says Turner. "But in general, the same principles would apply."

All this means we could be characterising habitable moons far sooner than habitable planets, he says. "If you are talking about anything remotely Earth-like, then I think 10 years is very optimistic, and 20 years maybe. But moons we could be working on within a few years."

Don't get your hopes of alien life up just yet, though, say both Heller and Turner. For a start, all ideas about exomoon habitability remain speculation until we have actually found some examples to test them on. And "until we find them we don't even know they are there. The solar system has lots of moons, but there's no guarantee that other systems do," says Turner.

But if we assume our solar system is representative of its kind, then it seems increasingly likely exomoons could be the first locations where we detect tantalising indications of life from afar. And that is a prospect far more exciting than any moon in the movies. ■

PLANTS OF PANDORA

Exomoons orbiting planets in other solar systems present us with many possible habitats – but not all are as lush as fictional creations.

RED DWARF MOON

Red dwarfs are the most abundant stars in our galaxy. Chances are these small, dim stars wouldn't illuminate lush green worlds. Photosynthetic life would have to draw light from as broad a range of the spectrum as possible, so is most likely to be black – as would life on a moon orbiting some distance from a sun-like star.

EARTH-LIKE MOON

A moon positioned further out than the stellar "habitable zone" – where temperatures are right for liquid water to exist – could still have Earth-like conditions. It would need to be large and get a tidal heating effect from its planet, and the mix of land and sea would be important. On a large watery moon, the oceans could be hundreds of kilometres deep and the pressures at depth too severe for life to get started. Overall light levels would be lower, too.

HOT ROCKY EXOMOON

Far away from its parent star, this large moon gets most of its energy from tidal forces that drive plate tectonics. Depending on how much water it started out with, there might not be much there. Hyperthermophilic bacteria and archaea that thrive at temperatures above 80 °C on Earth could provide the best indication of what any life might look like.

THE EXTREME TIDAL MOON

If a moon were orbiting particularly close to a large planet, the tidal forces could be enormous. Here, as with Jupiter's Io, the rocky surface would bulge up and down by more than 100 metres, and the intense volcanic activity and searing heat would probably rule out life.

With thanks to Lewis Dartnell, research fellow in astrobiology at the University of Leicester, UK

THE DWARF THAT GREW TOO BIG

We thought we knew how supernovae worked – until one came along and blew up the rule book, says **Colin Stuart**

WHEN Andy Howell announced what he had found, a gasp filled the lecture hall. "Nobody saw it coming," he says.

That was in Prague in 2006. Howell, now at the University of California, Santa Barbara, was at a meeting of the International Astronomical Union presenting his team's latest observations of the exploding stars known as type-1a supernovae. We think we know what makes these stellar bombs tick – and a lot rides on us knowing it. Above all, they detonate with a similar brightness, a fact that allows us to calibrate distance in the universe. Observations of type-1a supernovae led 17 years ago to one of the landmark discoveries of modern cosmology: that the expansion of the universe is accelerating, fuelled by a shadowy agent since dubbed dark energy.

"We think we know what makes these stellar bombs tick – and a lot rides on us knowing it"

Except if what Howell was saying was right, things weren't that simple. He and his colleagues had seen a monstrously bright supernova that exploded all the rules. It did not mean the accelerating universe was wrong – but unmasking whatever was responsible was going to be even harder than we thought.

To understand why this was so we need to wind back to the summer of 1930, and a boat afloat on the Indian ocean. On board was the 19-year-old prodigy Subrahmanyan Chandrasekhar, en route from Madras to take up a doctoral position as an astrophysicist at the University of Cambridge. To while away the time, he did a few calculations to resolve a mystery surrounding the existence of a type of star called a white dwarf.

White dwarfs are a cosmic curiosity. The stability of any star relies on a delicate balance between the inward pull of gravity and some form of internal resistance. In an ordinary star, this is supplied by the thermal pressure of nuclear fusion reactions at its core. When a star begins to run out of fuel, gravity wins out and the star starts collapsing.

This collapse does not continue forever. When the diminishing star reaches about the size of Earth, electrons within it offer up their own form of resistance, called degeneracy pressure. This comes about because if the electrons were squeezed any further, they would be forced to occupy the same energy state as each other, something a quantum rule called the Pauli exclusion principle forbids. Unable to be corralled any further, the electrons prop up a semi-collapsed stellar remnant: a white dwarf.

SIMON DANAHER

That explained how these mysterious objects came to be, but Chandrasekhar's calculations also revealed a limit to their size. If the collapsing object's mass tipped the scales at more than 1.4 times that of the sun, degeneracy pressure would not be sufficient to counteract its gravity. It would evolve into a much denser object: a neutron star or even a black hole.

At the time, to mention black holes was astronomical blasphemy, and the opposition of luminaries of the age, such as the director of the Cambridge Observatory where Chandrasekhar was bound, Arthur Eddington, meant Chandrasekhar's work was initially ignored. It took more than 50 years for full recognition to come his way, when he was awarded a share of the 1983 Nobel prize in physics for his work. The ceiling of 1.4 solar masses, known as the Chandrasekhar limit, is now universally accepted, and has been borne out time and again by observations.

What bearing does this have on supernovae, dark energy and the rest? That lies in the fact that it is rare for stars to live out a solitary existence; they are more often found orbiting each other in a binary system. If one of this gravitationally conjoined pair collapses to form a dense white dwarf, it can begin to devour material from its companion star, bulking itself up. In this way a white dwarf can approach the Chandrasekhar limit even ›

after it has formed. As it does so, it can further contract, heat up and reignite nuclear fusion. The white dwarf is then ripped apart in the blink of an eye, exploding as a type-1a supernova.

Other types of supernova exist, with chemical signatures that indicate origins in different types of stars. But because type-1a supernovae are always filled with the same amount of fuel, they always explode with the same intrinsic brightness. Their brightness as observed by us is then just a measure of how far away the explosion occurred. This apparent brightness can be used as a "standard candle" to determine the distance to the supernova's host galaxy.

This chain of reasoning led to the shock discovery, made independently by two teams in 1998, that certain supernovae are further away than they should be. Another measure of the amount of space between us and a cosmic object is its redshift: as light travels towards us from distant parts of the universe, the expansion of the intervening space stretches it to longer, redder wavelengths. The redshift of type-1a supernovae showed consistently that space had expanded more than we would expect given the supernovae's distance as measured by their brightness (see diagram, below right). The effect was so convincing and so consistent that there seemed to be only one possible conclusion: the space between us and them had started to expand faster, pushing the supernovae to ever greater distances. This was a turn-up for the books. If anything, we had thought that gravity's merciless pull would be gradually slowing the universe's growth. Not so: the universe was accelerating away from us.

Sacred violation

If that was a shock, what Howell presented in Prague was a counter-shock. He was describing a type-1a supernova that had exploded three years earlier, known by the trip-off-the-tongue name of SNLS-03D3bb. The sting in his tale was that the supernova's extreme brightness indicated a fuel stock close to two solar masses. Chandrasekhar's unbreakable limit had seemingly been broken. "I was saying that we've found something that appears to violate this practically sacred Nobel-worthy calculation that every astrophysicist knows," says Howell.

While theorists debate how that might be possible (see "One dwarf or two?", left), more of these "super-Chandra" supernovae have been popping up. Over the past seven years,

RAY BERTRAM/STEWARD OBSERVATORY

"With no idea what causes the oddball explosions, we cannot tell where they are leading us astray"

the intermediate Palomar Transient Factory (iPTF) has been scanning the skies above California and classifying supernovae. Of over 1000 type-1a explosions, fewer than 1 per cent are confirmed rule-breakers. Not many, but enough to raise a pressing question: where does it leave ideas of an accelerating universe ?

First up, it almost undoubtedly does not change the bald fact. Since the supernova measurements, dark energy's presence has been gleaned from other independent sources such as the patterns of fluctuations in the cosmic microwave background, the radiation left over from the big bang.

What it does is threaten to foil attempts to unmask dark energy's identity. One leading contender is the cosmological constant. Einstein infamously introduced this quantity into his equations of general relativity in 1917 to act as a buffer against gravity and maintain the static universe that he and most others at the time believed to exist. He realised he had erred in the 1920s when the universe was found to be expanding from an origin in a big bang, something perfectly explicable without a hand-spun patch on the equations. But after the supernova revelations, a gravity-defying constant with the same density in all of space provided a neat way to explain why the universe's expansion has been picking up pace: as the amount of space increases, there is more of the constant, so its effects increase.

If dark energy really does take the guise of a

ONE DWARF OR TWO?

Upasana Das thinks she knows how the white dwarf stars that cause type-1a supernovae can get so much more massive than the 80-year-old Chandrasekhar limit allows (see main story). "Chandrasekhar didn't consider highly magnetised white dwarfs," says Das, of the Indian Institute of Science in Bangalore.

Das has shown, together with her colleague Banibrata Mukhopadhyay, that a concentrated magnetic field provides an extra quantum-mechanical effect known as Landau quantisation within a white dwarf. This gives electrons additional resistance against gravity, staving off collapse up to a mass of 2.6 suns, rather than the 1.4 suns suggested by Chandrasekhar. The Sloan Digital Sky Survey, a cosmic trawl that has scanned more than a quarter of the sky, has uncovered several white dwarfs that scientists believe may have sufficiently strong magnetic fields to activate the mechanism.

An earlier suggestion was that a rapidly rotating white dwarf might be better able to withstand gravitational pressures and accumulate more mass before exploding. But models of rotating stars suggest they would have a different chemical composition from that seen in massive supernovae, says Stefan Taubenberger of the Max Planck Institute for Astrophysics in Garching, Germany.

His own idea for overbright type-1a supernovae is more radical. The standard picture has a single white dwarf devouring a companion until it reaches the Chandrasekhar limit and explodes. Taubenberger's scenario has two white dwarfs each of about 1 solar mass that initially coexist peacefully. But one is slightly larger than the other and starts to tear material from its partner. On reaching the Chandrasekhar limit it explodes, with its ejected material ploughing into the remains of the diminished partner and making it glow brightly. "You can produce a lot of additional luminosity because some of the explosion's kinetic energy is converted into light," says Taubenberger.

As yet these are just ideas. "There is a whole mess of data out there and observation needs to catch up with theory," says Richard Scalzo of the Australian National University in Canberra. In April 2013, Xiaofeng Wang, then at Tsinghua University in Beijing, China, showed that the light spectra from over 100 well-defined type-1a supernovae suggest their progenitors have two distinct chemical compositions. If that is confirmed, it might be that type-1a supernovae are not even one type at all.

When completed, the LSST will use one of the world's largest mirrors to hunt for supernovae

cosmological constant, its value must never change over space and time. Other suggested forms for dark energy, such as an energy field called "quintessence", would have different characteristics, for example becoming more diluted as space stretches. This suggests a way to unmask the agent of cosmic acceleration. "We need to look at dark energy's evolution over its entire history," says Richard Scalzo of the Australian National University in Canberra – from the close-by recent universe to the far-flung regions that reveal the universe in its infancy. Supernovae, which have been around for almost as long as stars, are the most direct way to do that. The super-Chandra supernovae urgently need to be eliminated from the data sets, so as not to skew the distance measurements.

That's where things get tricky. With no idea what causes the oddball explosions, we cannot tell where they might be leading us astray. There are a few indications that the super-Chandra explosions tend to happen in places with low levels of elements heavier than hydrogen and helium, says Stefan Taubenberger of the Max Planck Institute for Astrophysics in Garching, Germany. That suggests the top-heavy interlopers might be more abundant in the early universe, before stars had had much opportunity to fuse many heavy elements. "My guess is their relative rate would be higher, but we don't have an idea of how much higher at the moment," says Mark Sullivan of the University of Southampton, UK.

The further away a supernova is, the harder it is to work out whether it is an anomaly: existing telescopes cannot provide an accurate enough spectrum of the light from the exploding star. Distant super-Chandras could already be masquerading as run-of-the-mill type-1a supernovae. "There is a real danger that these objects might creep in to the data and not be recognised," says Taubenberger.

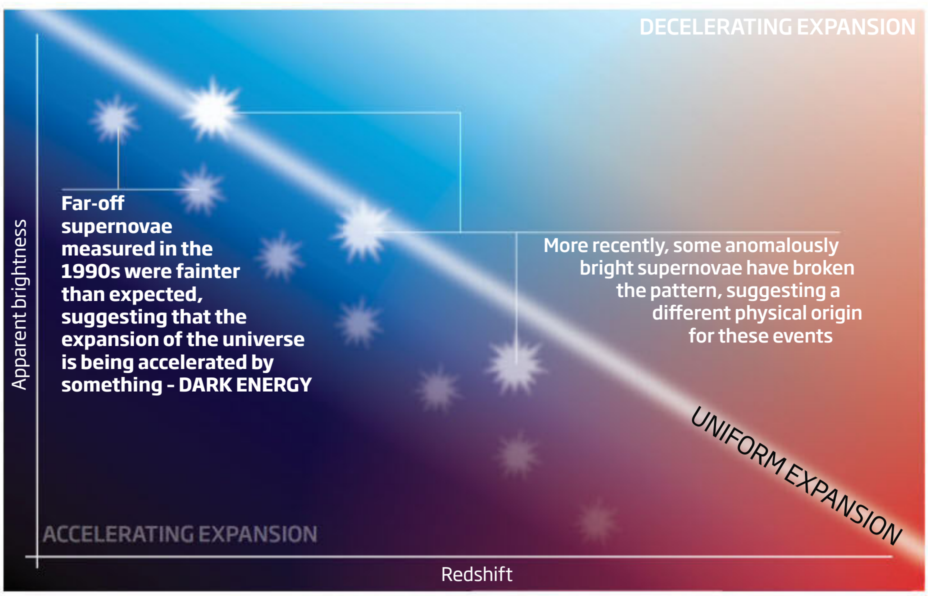
The present clutch of super-Chandras probably represent extreme cases: there is likely to be a sliding scale of rule-breakers between the standard supernovae and the known band of rebels. These will be even harder to weed out. Sky surveys such as the iPTF and the Nearby Supernova Factory, which uses a telescope atop Mauna Kea in Hawaii, currently log thousands of type-1as, but classifying them more effectively requires knowledge of the subtle differences between millions of exploding stars.

That is why a plan is afoot to kick supernova surveys into overdrive. Construction has started on the Large Synoptic Survey Telescope, a massive instrument high in the Chilean Andes. Its primary mirror, 8.2 metres across, has already been cast and ground, and will eventually be attached to a 3.2-gigapixel digital camera, one of the largest ever made. The LSST will be able to examine 10 square degrees of the sky at a time, equivalent to the space nearly 50 full moons would take up in the sky. At a rate of 800 snaps per evening, it will cover the entire sky in the course of just three nights, allowing it to create a database of up to a million supernova explosions over 10 years, as well as do other things such as keep a lookout for potentially hazardous near-Earth asteroids.

But it will be at least a decade before we have access to that database. In the meantime, without certain knowledge of what triggers the anomalous supernovae it is hard for astronomers to know whether they are doing the right things for the right reasons. "We're making blind corrections at the moment based on empirical observation, not a deep astrophysical understanding," says Howell. Nine years on from that moment in Prague, the shock waves from his explosive announcement continue to reverberate. ■

Surprising supernovae

In a universe expanding at a fixed rate, type-1a supernovae would be expected to look dimmer as redshift, a measure of their distance from us, increases. But observations have thrown up some surprises



Secret supernovae

When stars explode without a visible trace, it takes something special to find them. Stuart Clark reports on the curious incidents of the missing supernovae

WHEN the final thing a giant star does is explode, briefly giving out more light than 100 billion ordinary stars put together, you would be forgiven for thinking that spotting them is pretty easy. Indeed, hundreds of these epic events are seen every year by the armies of astronomers that scan the skies in search of them.

Yet these are just the tip of the iceberg. When astronomers scale up to the number of supernovae they expect to be taking place throughout the entire universe they reach a mind-boggling number: thousands of exploding stars every hour. In the time it has taken to read this introduction, five massive stars have destroyed themselves somewhere in the universe. The energy from these blasts is now racing across space, perhaps to encounter Earth in millions or even billions of years.

But there is a problem. "Up to half the supernovae are going missing," says John Beacom, an astronomer at Ohio State University in Columbus. The big question is, what is happening to these stars? Are they simply disappearing without trace: there one minute and gone the next, or are we simply failing to see their explosive finale?

Understanding supernovae isn't some trivial piece of celestial accounting. Supernovae are the engines of cosmic change. They shape galaxies, sometimes by triggering new stars to be born and at other times by halting star formation in its tracks. For a galaxy small enough, a volley of supernovae can blow it apart.

Perhaps most importantly for us, supernovae help to seed the universe with the atoms that make planets and life possible.

Stars live predictable lives. They are born in clouds of interstellar gas and dust and play out their years governed by the laws of physics. Massive stars, ones that are more than 8 times as massive as the sun, exist for a few million to tens of millions of years – the blink of an eye in cosmic terms – then explode as supernovae. A supernova begins when the core of the massive star becomes so large that it is no longer able to support its own weight (see "The dwarf that grew too big", page 103). The core collapses from roughly the volume of the Earth to the volume of an asteroid, creating a ball of neutrons just 10 to 15 kilometres across – a neutron star. With its heart suddenly crushed, the rest of the star comes crashing down on top.

Gone without a flash

This inrush of gas strikes the neutron star, creating a shock wave that heads outwards. From here, two things can happen. In the first scenario, the shock wave is powerful enough to move outwards through the downpour of material and blast huge quantities of gas into space, creating a supernova explosion and leaving behind a neutron star and a nebula of shining gas that persists for centuries.

In the second scenario, the shock wave simply stalls. More and more gas falls down on to the neutron star until it eventually collapses into a black hole. Astronomers call this a "failed supernova". With no supernova, the star will simply disappear: there one moment and gone the next. "It's like being at a concert and seeing all the

lighters in the air, and then one of those lighters just goes out," says Beacom.

So we know what happens, in theory. The problem comes when we tot up the numbers. Astronomers have developed numerous techniques for measuring the rate at which stars of all sizes are born over the aeons. They have seen that this rate changes so slowly over the course of billions of years that for massive stars living such short lives, the death rate must match the birth rate. It's when astronomers add together the observations of supernovae and black holes that the death rate comes up well short.

Of course, there could be a simple explanation. Some supernovae may be going off behind great banks of cosmic dust and so be hidden from our view, while others are intrinsically faint. Black holes are fiendishly difficult to spot too. Unless they happen to be close enough to rip another star to pieces, they are essentially invisible (see "Signatures of the invisible", above).

To make progress, we need a new way to study supernovae. And astronomers believe the answer lies with ghostly particles called neutrinos. All supernovae, from the failed to the brightest, emit neutrinos. As much as 99 per cent of a supernova's energy is carried out into space by neutrinos – even by the most luminous supernovae. "Neutrinos are what a supernova is really all about," says George Fuller, a theoretician at the University of California, San Diego, "The energy of the optical explosion is pretty small in comparison."

Supernovae neutrinos are produced during the maelstrom of the star's initial collapse as the neutron star is built. During this tumultuous event and under eye-watering pressure, electrons are forced into the atomic nuclei, where they combine with the protons to form the neutrons. Each of these reactions gives off a neutrino.

They aren't alone. Neutrinos are streaming through us at all times. They come from a variety of sources on Earth, notably radioactive decay, lightning strikes and nuclear reactors. The sun drenches us in neutrinos too and then there are the cosmic rays that hit the atmosphere and produce showers of particles, including neutrinos. The reason you don't feel trillions of neutrinos pouring through your body at this moment is because they interact so weakly with matter.

To catch one, we need giant detectors like the Super-Kamiokande experiment deep under mount Ikenoyama in Japan. Super-K comprises a huge tank filled with 50,000 tonnes of ultra-pure water and works by detecting the fleeting pulse of light given out on the rare occasions when a neutrino collides with one of the water molecules. Such detectors have taught us much about the nature of neutrinos themselves. But when it comes to neutrino astronomy, they are more akin to Galileo's spyglass than the Hubble Space Telescope.

The sun is such a huge source of neutrinos that distinguishing neutrinos from another celestial object has so far proved next to impossible. Astronomers have only managed to do it once, back in 1987 when a supernova exploded in the nearby Large Magellanic Cloud galaxy, 170,000 light years away. Super-K had not been built back then but its forerunner, Kamiokande II, was in operation. It captured just 12 neutrinos while the Irvine-Michigan-Brookhaven detector under Lake Erie in Ohio bagged eight.

Although small in number, they confirmed the overall picture of the star's core collapse resulting in a burst of neutrinos. Since then, no other supernova has gone off near enough for its neutrinos to be detected, despite significant advances in our ability to capture them over the ensuing decades.

Supernovae in our galaxy have proved rare in the last few centuries, with the last one being seen by Johannes Kepler in 1604. This is frustrating because Super-K would detect an estimated 10,000 neutrinos if a supernova were to explode in the Milky Way. With such a haul of neutrinos, astronomers could begin to check their theories in detail.

All is not lost, though. The next generation

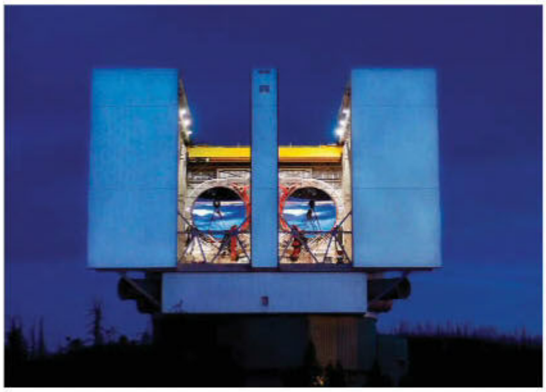
"Neutrinos given out by each and every supernova throughout history will still be in space"

SIGNATURES OF THE INVISIBLE

The number of black holes in the Milky Way could tell us what proportion of dying stars fail to go bang supernova-style. The trouble is that not every black hole will be visibly stripping matter from a nearby companion star to make them detectable. They are destined to remain forever invisible.

Andrew Gould at Ohio State University in Columbus begs to differ. He has devised a way of searching for some of our galaxy's black holes using the European Space Agency's Gaia space telescope. Launched in December 2013, Gaia will repeatedly measure the position of a billion stars in the Milky Way. Gould has calculated that the motion of wobbling stars can reveal whether an orbiting black hole is producing the movement. "It's a clean and simple experiment to perform," he says.

As for the wider cosmos, Christopher Kochanek – also at Ohio State University – is part of a team hoping to see a black hole form. They are doing this by looking for stars that simply disappear. The Survey About Nothing, as it is called, uses the Large Binocular Telescope at Mount Graham International Observatory in Arizona (pictured), to monitor a million massive stars in nearby galaxies. Such stars are expected to live only for a million years, so Kochanek and his colleagues are hoping for an average of one stellar death among their sample every year. The question is: will the unlucky stars explode or simply disappear? The survey has been running for six years and so far has identified one potential candidate for a vanishing supernova, with the hope that more will emerge as the survey continues.


LBT

of neutrino detectors will drastically extend our reach beyond the Milky Way and its environs. Of the devices on the drawing board and searching for funding, the most advanced is Hyper-Kamiokande, the proposed big brother of Super-K. It would be 20 to 25 times larger than Super-K and be capable of detecting individual supernovae bursts out to millions of light years away, bringing other large galaxies into view and leading to an expected detection rate of a supernova neutrino burst at least once a decade.

With such capacity, sooner or later, a neutrino burst will be detected that astronomers cannot find with their telescopes; in other words, a failed supernova. "You should hope to get one failed supernova per decade, about the same as the detection rate for a normal supernova," says Cecilia Lunardini at Arizona State University in Tempe, who has been investigating how best to detect some of the elusive particles.

With these observations in hand, a direct comparison with the neutrinos from a successful supernova will be possible. Computer simulations already suggest that neutrinos are the key to whether the supernova explosion triggers or fails. Zoom into the finer details of the simulations and you find that the outward moving shock wave stalls but can sometimes be revitalised if a tiny fraction of the neutrinos streaming out from the nascent neutron star is absorbed in the dense material that accumulates behind the stalled shock wave. With enough power, the shock wave can be made to race off through the rest of the star and blow it to pieces.

The simulations also tell us that neutrinos coming from failed supernovae should be more energetic than those from exploding ones. The reason is that the collapses that ultimately form black holes may be hotter, more extreme affairs than those forming neutron stars. "If we see higher-energy neutrinos we will know that failed supernovae are taking place," says Lunardini.

Neutrinos uncovered

The next generation of neutrino detectors should tell us more. They should be able to reveal the history of supernovae throughout the universe. This is because the weakly interacting characteristic of neutrinos means that they hang around for aeons. They cross the universe mostly passing unhindered through the stars and planets with the result that the majority of the neutrinos given out

"Neutrinos are what a supernova is all about. The visible explosion is small by comparison"

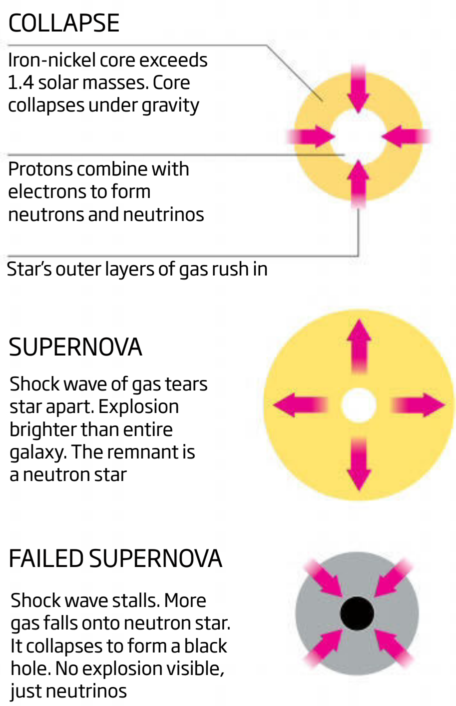
by each and every supernova throughout history will still be in space. They will exist in a vast sea of neutrinos called the diffuse supernova neutrino background (DSNB), which contains about a tenth of the energy density of the cosmic microwave background radiation left over from the big bang. The neutrinos in the DSNB will carry a range of energies. By comparing the spread of energies to those seen in the individual supernovae neutrino bursts, researchers will be able to work out the proportion of successful to failed supernovae.

Detectors like Hyper-K should routinely detect the DSNB. "It's a new frontier that we hope to see in the next decade or so," says Lunardini.

We may not have to wait quite so long. Tantalisingly, calculations suggest that water-based neutrino detectors such as

Death star

When a massive star has burned all its fuel, it can make a spectacular exit as a supernova or fail to ignite



Super-K are already right at the edge of detecting the DSNB. A few neutrinos from it are probably being caught every year but they are swamped by a background signal of neutrinos produced in the atmosphere when cosmic rays strike.

Luckily there is a solution. Neutrinos come in three types, or flavours, depending on how they are produced. For example, neutrinos produced in supernovae are electron-neutrinos, whereas twice as many muon-neutrinos are created in the atmosphere than electron-neutrinos. Only electron-neutrinos are revealed when a neutrino passes through a detector filled with ultra-pure water, as Super-K is. However, other experiments have revealed all three types of neutrino by dissolving salt in heavy water, which is made from a heavier form of hydrogen consisting of a neutron as well as a proton.

To Beacom and his colleagues, these different capabilities suggested a way to find the DSNB. The answer lay with the silvery-white metal gadolinium. Dissolving a soupçon of it into regular water can make any detected DSNB neutrinos give out a unique signal; first the burst of light that indicates the capture of the neutrino by a proton in the water, followed 20 nanoseconds later by a gamma ray with a distinctive energy. The gamma ray comes about because the neutrino interaction also produces a neutron that is captured by the gadolinium, which emits gamma radiation as a result.

So promising is this approach that the Kamiokande collaboration agreed to spend more than $4 million on a test facility known as EGADS, short for "evaluating gadolinium's action on detector systems". The test went so well that the team behind the main Super-K detector officially gave gadolinium their approval in June 2015. The first DSNB detections could be only a few years away, says Beacom.

Lunardini agrees that it could give us the first hints of the DSNB but to achieve the high numbers of neutrinos needed for a detailed analysis she says we'll need to wait for the next generation of neutrino detectors. Once astronomers have that, they can really begin to work out why stars explode.

"Supernovae confounded the ancient astrologers, now they are confounding modern astronomers," says Beacom.

But thanks to the growing confidence of the neutrino experimenters, there is now a real chance for progress. Nature is conducting thousands of experiments every hour before our eyes. All we have to do is watch and learn. ■

Quark stars

When neutron stars melt, what's left behind is truly strange. Anil Ananthaswamy reports

ON 22 September 2012, the website of The Astronomer's Telegram alerted researchers to a supernova explosion in a spiral galaxy about 84 million light years away. There was just one problem. The same object, SN 2009ip, had blown up in a similarly spectacular fashion just weeks earlier. Such stars shouldn't go supernova twice, let alone in quick succession. The thing was, it wasn't the only one, the next year another supernova, SN 2010mc, did the same.

One of the few people not to be bamboozled was Rachid Ouyed. "When I looked at those explosions, they were talking to me right away," he says. Ouyed, an astrophysicist at the University of Calgary in Alberta, Canada, thinks that these double explosions are not the signature of a supernova, but something stranger. They may mark the violent birth of a quark star, a cosmic oddity that has only existed so far in the imaginations and equations of a few physicists. If so they would be the strongest hints yet that these celestial creatures exist in the cosmic wild.

The implications would be enormous. These stars would take pride of place alongside the other heavenly heavyweights: neutron stars and black holes. They could help solve some puzzling mysteries related to gamma-ray bursts and the formation of the heftiest elements in the universe. Back on Earth, quark stars would help us better understand the fundamental building blocks of matter in ways that even machines like the Large Hadron Collider cannot.

Astrophysicists can thank string theorist Edward Witten for quark stars. In 1984, he hypothesised that protons and neutrons may not be the most stable forms of matter.

Both are made of two types of smaller entities, known as quarks: protons are comprised of two "up" quarks and one "down" quark, whereas neutrons are made of two downs and one up. Up and down are the lightest of six distinct "flavours" of quark. Add the third lightest to the mix and you get something called strange quark matter. Witten argued that this kind of matter may have lower net energy and hence be more stable than nuclear matter made of protons and neutrons.

Quark nova

If so, we might all start decaying into strange matter. But don't fret. You either need to wait around longer than the age of the universe for the stuff to form spontaneously, or find somewhere with the right conditions to start the process. One place this could happen is inside neutron stars, the dense remnants of certain types of supernovae.

When a star many times more massive than the sun runs out of fuel, its inner core implodes. The outer layers are cast off in a spectacular explosion. What's left behind is a rapidly spinning neutron star, which as the name implies is made mainly of neutrons, with a crust of iron. Whirling up to 1000 times per second, a neutron star is constantly shedding magnetic fields. Over time, this loss of energy causes the star to spin slower and slower. As it spins down, the centrifugal forces that kept gravity at bay start weakening, allowing gravity to squish the star still further.

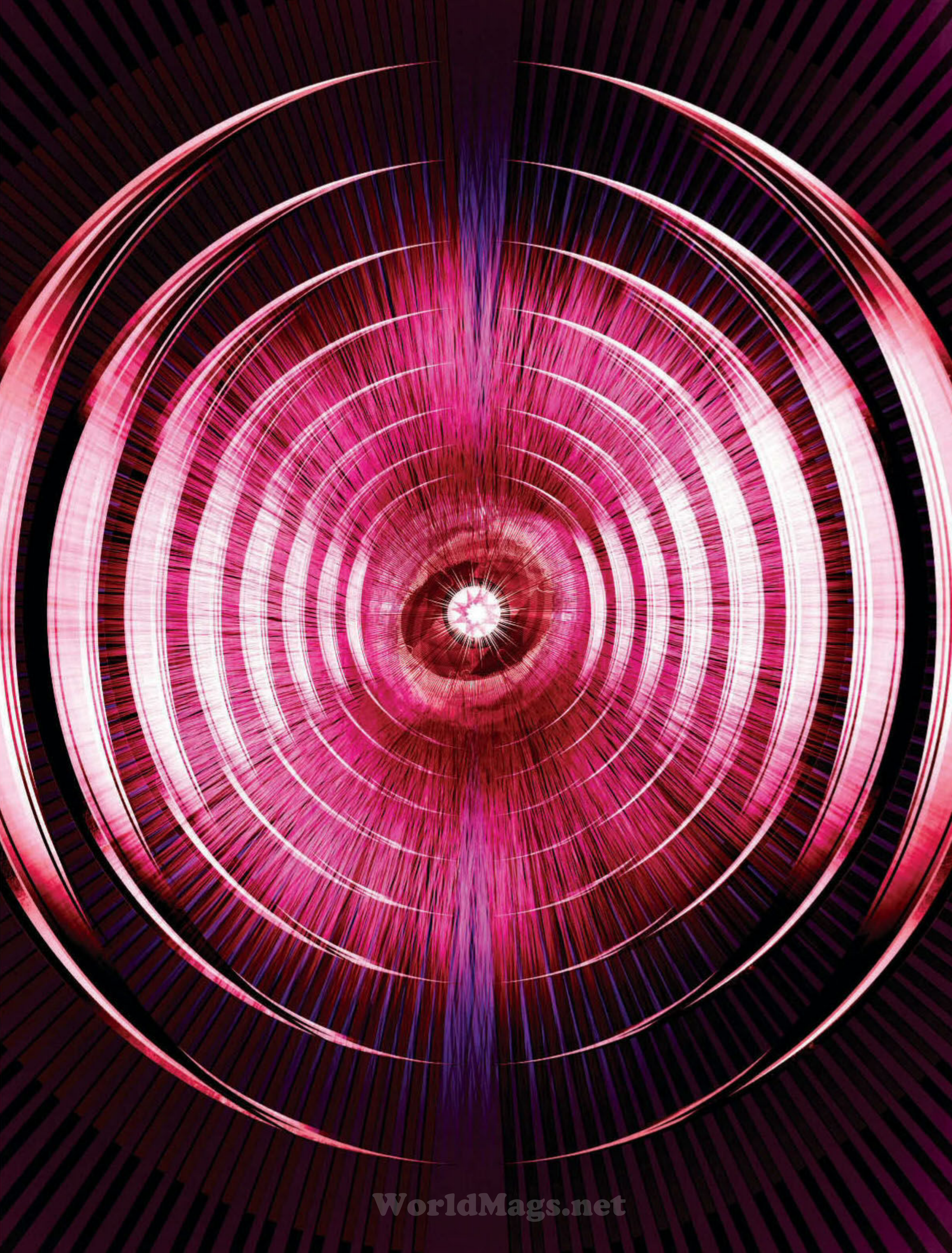
In what is a blink of an eye in cosmic time, the neutrons can be converted to strange quark matter, which is a soup of up, down and strange quarks. In theory, this unusual change happens when the density inside the neutron star starts increasing. New particles called hyperons begin forming that contain at least one strange quark bound to others.

However, the appearance of hyperons marks the beginning of the end of the neutron star. "Once you start to form hyperons, then you can start the nucleation of the first droplet of strange quark matter," says Giuseppe Pagliara of the University of Ferrara in Italy. As the density in the core continues to increase, the star's innards "melt", freeing quarks from their bound state. In fact, a single droplet of strange matter is enough to trigger a runaway process that converts all the neutrons. What was a neutron star turns into a quark star.

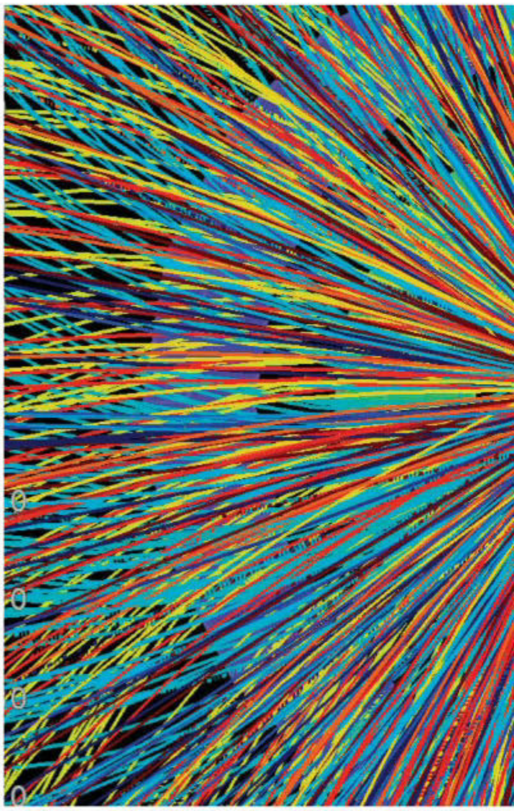
Of course, this assumes that Witten is correct about strange quark matter being more stable than neutrons. No one has yet proved him wrong, but it is a tough idea for some to swallow. "More conservative thinkers are just not open to the idea that free quarks exist in neutron stars," says Fridolin Weber, an astrophysicist at the San Diego State University in California.

Not so the daring ones. Ouyed, for instance, has been trying to convince his fellow astrophysicists of the existence of quark stars for more than a decade. Not only do these intrepid few think that quarks can exist

MATT MURPHY



"Quark stars can help us understand the fundamental building blocks of matter in ways that even the Large Hadron Collider cannot"


CERN/SCIENCE PHOTO LIBRARY

freely inside neutron stars, they have even thought about what comes next. "We all agree that if quark stars exist, then the conversion of normal, ordinary matter into a quark star will be a very exothermic process, a lot of energy will be released," says Pagliara. "How this energy is released is a matter of debate."

On one hand, Pagliara and his colleagues have done extensive simulations to show that this conversion will happen in a matter of milliseconds. In what he calls a "strong deflagration", the neutron star burns up as it turns into a quark star. There is no explosion.

Ouyed, on the other hand, begs to differ. His team's simulations show that the conversion is most likely to be an extremely violent process. The seed of strange quark matter spreads until it reaches the outer crust of the neutron star. As the part of the star that has been turned into quark matter separates from the iron-rich crust, it collapses. The collapse halts when the inner core becomes incredibly dense and rebounds, creating a shock wave that spreads outwards at speed. Much as in a supernova, the iron-rich crust and leftover neutrons are ejected in another spectacular explosion – a "quark nova".

Hurtling through space, the quark nova ejecta then slam into the earlier supernova remnants, causing them to light up again, as they did after the explosion of the original, conventional star. What's left behind is a quark star. "It was very hard to find solutions where the entire neutron star turned into a quark star, in just a puff with no explosion," says Ouyed.

Double explosion

Depending on the mass of the star before its first explosion, the second blast could occur anywhere from seconds to years after the original supernova. Too soon, and the two explosions would merge, appearing as one blast, smeared out in time. Too late, and the supernova ejecta would have dispersed long before the detonation of the quark nova, and there would be no re-brightening.

But if the timing is just right, the outcome should be observable. In 2009, Ouyed's team predicted that if the quark nova goes off days or weeks after the supernova, there should be two peaks in energy: the first being the supernova explosion itself, and the second being the reheating of the supernova ejecta. The objects SN 2009ip and SN 2010mc matched predictions in ways almost too good to be true.

SN 2009ip had its first major explosion in early August 2012, and 40 days later flared up again. SN 2010mc was eerily similar in its outbursts, showing a double explosion in which the peaks were about 40 days apart. While other researchers continue trying to explain these unusual observations using their tried-and-tested models of supernovae, Ouyed is convinced that we have witnessed quark stars being born.

Oddly, it is the first peak in both events that convinces him. If these have all the characteristics of a regular supernova, it makes the second boom harder to explain using conventional arguments. "When you look at the first ejecta, it looks like a duck and walks like a duck: it's a supernova," says Ouyed. "Then what's the second one?"

He points the finger at quark novae. "We just applied our model of the dual shock quark nova, and it was actually easy to fit," he says. "That's the beauty of it."

While Pagliara and Ouyed's teams disagree on whether the transition from a neutron star to a quark star is explosive, they do agree that space should be littered with quark stars. How should we look for them?

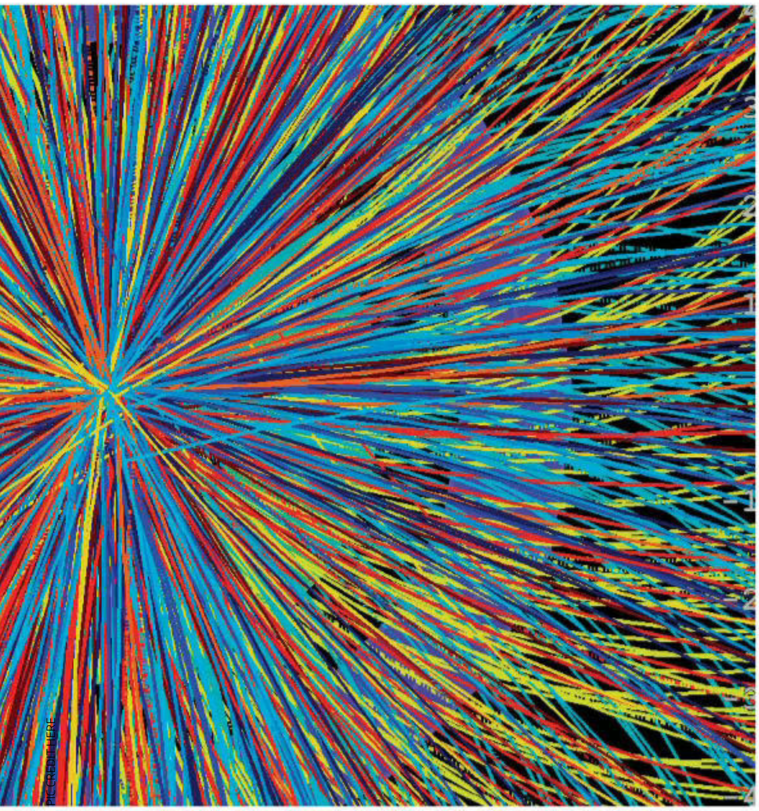
We might be mistaking some of them for neutron stars, says Pagliara. Most neutron stars weigh as much as 1.4 suns or slightly more. The best studied examples, orbiting each other in systems called Hulse-Taylor binary pulsars, certainly follow this pattern. Both neutron stars involved weigh in at 1.4 solar masses. However, Pagliara is bothered by two discoveries of neutron stars that tip the scales at 2 solar masses each. "It's difficult to reach this mass with normal particle components like neutrons, protons and hyperons," he says.

This has to do with a property of matter called its equation of state. Equations of state describe how matter behaves under changes in physical conditions, such as pressure and temperature. Hyperons, which are precursors to strange quark matter, have a "soft" equation of state. Their existence in the dense core of a neutron star makes the star more compressible, causing it to shrink in size more readily under pressure.

Astronomers estimate that neutron stars are about 10 kilometres across – but squeezing 2 solar masses into an object of such size would end up creating a black hole. Pagliara says that compact stars weighing 2 solar masses or more have to be bigger, or put another way, the matter has to be "stiffer" so that gravity cannot compress it as much. There is one candidate with a stiffer equation of state: strange quark matter.

Pagliara and his colleague Alessandro Drago and others claim that the compact stars we have spotted come from two families. The smaller ones must be the run-of-the-mill neutron stars. The larger ones must be quark stars. The only way to verify this claim is to measure their masses and also measure their radii to the nearest kilometre. A proposed European satellite mission called the Large Observatory for X-ray Timing could do just that. Its aim is to measure the equation of state for compact objects – and thus differentiate between neutron stars and quark stars.

Meanwhile, Ouyed's team is concentrating



Cosmic wild: particles containing strange quarks emerge from collisions of heavy ions

on predictions based on their quark nova model. One prediction has to do with the creation of heavy elements in the universe. Once a massive star goes supernova, weighty elements are synthesised in a matter of milliseconds, when neutrons are absorbed into iron nuclei. These neutron-rich nuclei are unstable and decay into elements further up in the periodic table when neutrons get converted to protons. "But the challenge with supernovae has always been to go to really heavy elements," says Ouyed. The iron and neutrons needed for the process are in short supply because most of them are left behind in the remnant neutron star.

The quark nova solves that problem. Its ejecta are a potent mix of neutrons and iron from the neutron star's crust, providing just the laboratory for synthesising the heaviest elements. Ouyed is urging astronomers to study double explosions carefully. His team predicts that the second blast should show the presence of elements heavier than atomic mass 130, elements which should be missing from the first explosion.

The conversion of a neutron star to a quark star could also solve another problem plaguing astrophysics: the source of some long-duration gamma-ray bursts, which are among the brightest events in the universe. On 9 July 2011, NASA's SWIFT gamma-ray satellite saw a burst with two spectacular peaks of emission, spaced 11 minutes apart. And the second was the stronger of the two. The traditional "collapsar" model of gamma-ray bursts relies on a star collapsing to a black hole. As the last remnants of the doomed star fall in, it is thought to result in such an emission. But 11 minutes is an eternity for a black hole – it's hard to make sense of the second peak.

Pagliara thinks his team has the answer.

"Space should be littered with quark stars. How should we look for them? We may be mistaking some of them for neutron stars"

According to their model, a neutron star converts to a quark star without an explosion. Yet there is still a tremendous release of energy, which Pagliara suspects goes into gamma rays. This could explain the second peak. "At the moment, and it's speculation, we think that this second event could be related to quark stars," he says. "If you want to see a possible signature of formation of quark matter, you should probably look at those gamma-ray bursts that have an activity long after the main event."

Quark world

Confirming the existence of quark stars and verifying their properties could have a huge impact on particle physics. Colliders like the LHC and the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory in New York have been smashing heavy ions head-on to create a state of matter called a quark-gluon plasma, where quarks are essentially free.

The best way to study this phase of matter is using a method called lattice quantum chromodynamics. But physicists have only been able to solve the equations of lattice QCD for high temperatures and low density – the conditions created at the LHC and the RHIC. The equations are intractable for other conditions. For instance, it is impossible to calculate the density at which protons and neutrons can melt into their constituent quarks at low temperatures.

Enter quark stars. First, if their existence is confirmed, it proves that quarks can exist freely at high densities and low temperatures, rather than bound up in hadrons – the catch-all name given to any particle made of quarks. Second, for the explosive quark nova model Ouyed's team has shown that the density at which quarks get freed is intimately linked to the time lag between the supernova and the quark nova. Measure the timing of the double explosion and you will glean important clues about conditions at the transition. "The quark nova is a very beautiful bridge that straddles the hadronic world and the quark world," says Ouyed. "It'd be a very nice tool to use for physics and astrophysics."

Weber agrees that quark stars, if they exist, would be a unique astrophysical laboratory. They would help us probe properties of matter in ways that we cannot do with the best colliders on Earth – in the domain of high densities and low temperatures. "This is a regime that is only accessible to stars, and only stars can tell us what will happen." ■

Fallen star?

Lonely planet?

Best of all worlds

Meet the cosmic object going from zero to astronomical hero, says Sarah Cruddas

AS IF space wasn't lonely enough, pity the brown dwarf. Compared with their stellar siblings, these astronomical objects are something of a failure. And while they have much in common with planets, they don't seem to fit in there either.

This awkward status as cosmic in-betweener means brown dwarfs are often overshadowed by their flashier counterparts, such as alien worlds or fiery supernovae. Yet not fitting in is precisely what makes brown dwarfs far more interesting and useful than we once thought.

As new evidence of these celestial outcasts emerges, they are challenging our ideas about the differences between planets and stars. Some have weather unlike anything seen before, from molten iron falling as rain to silicate snow. And the traits they share with exoplanets means that we can learn things that telescopes pointed at alien worlds cannot reveal. The most unloved destinations in space are fast becoming the new cosmic "it" objects.

The existence of brown dwarfs was first suggested in 1962 by Shiv Kumar at the ›

Impressions of brown dwarfs in all their intriguing hues

NASA Goddard Institute for Space Studies in New York City, who had wondered how small a star could be. Below a certain size, Kumar calculated, you would end up with degenerate objects with too little mass to sustain hydrogen fusion, and they would fizzle out.

Kumar called these hypothetical objects "black dwarfs", but the name proved problematic. In the 1970s, astronomer Jill Tarter pointed out that the term also referred to a dark, cooling star near the end of its life. Various other names had been proposed, such as "planetar", "still-born star" or "substar", but Tarter argued for "brown dwarf". She knew

"After years of speculation, the first brown dwarf might have enjoyed more fanfare, but it was overshadowed"

they couldn't actually be brown (see "True colours", opposite page), but she felt labelling them with a composite colour was appropriate since their actual colour was going to be difficult to observe due to their feeble radiation.

Tarter was half right: their feeble radiation meant none was spotted for another 20 years. In this period, brown dwarf research stalled. Then, in 1995, Gliese 229b popped into view. About 19 light years away, this brown dwarf was found thanks to advances in infrared telescopes and by switching the search to younger star systems, within which any objects are brighter and easier to spot.

The dwarf had a mass between 20 and 50 times that of Jupiter, and a relatively cool surface temperature of 680 °C. Did this bring brown dwarfs into vogue at last? Not quite. After three decades of speculation, the find might have had more fanfare, but it was announced at the same conference as the discovery of the first exoplanet, so was overshadowed.

Still, for a small group of dedicated researchers, it offered an intriguing puzzle: Gliese 229b was a star, but it had a planet's atmosphere. "It was clearly very different … its luminosity, its spectral analysis, the fact that it had methane in it," says Rebecca Oppenheimer, astrophysics curator at the American Museum of Natural History, who was part of the team who found it. The only thing they had to compare it with was Jupiter, but it wasn't a gas giant.

As more brown dwarfs emerged with similarly puzzling traits – we have now found more than 1200 – it sparked debate about how to classify them. Since humans first looked to the heavens, there has always been a separation between stars and planets. Brown dwarfs challenge these ideas. "It depends on what question you ask, as to whether they are a planet or a star. They blur the distinction between the two," says Ben Burningham, currently at the NASA Ames Research Center in Moffett Field, California.

BABAK TAFRESHI/TWAN/SPL; PREVIOUS PAGE, TOP AND BOTTOM: MARK GARLICK/SPL; MIDDLE: NASA/JPL-CALTECH

Brown dwarfs are born from the collapse of a gas cloud, just like stars, so share some features with their stellar relations. They have magnetic spots like stars, and some even emit radio emissions like pulsars. They are also dense enough to fuse a finite tank of deuterium at the start of their lives. This produces faint infrared radiation, as does the conversion of gravitational energy into heat. Gradually, though, they cool through their lifetimes, says Burningham, "like an ember plucked from a fire". This makes them much colder – with some reaching temperatures as low as 27 °C.

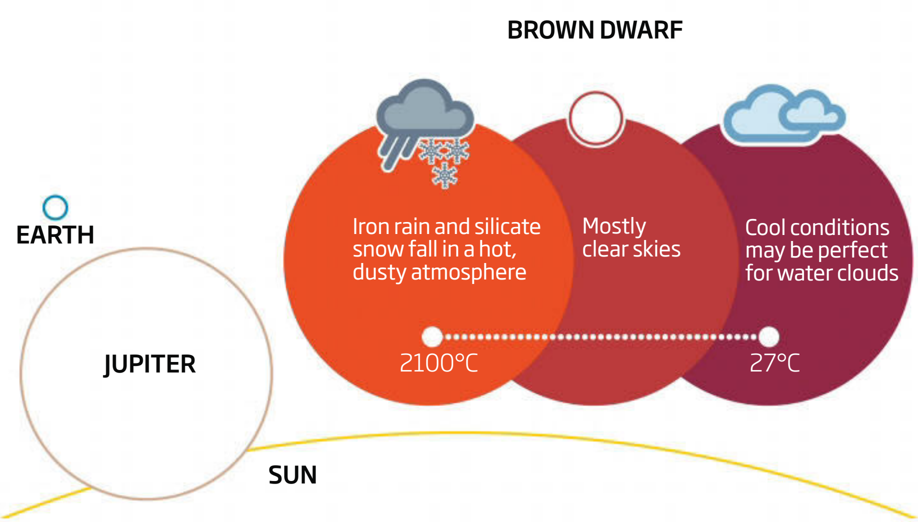
So should we think of them more like planets? Brown dwarfs are significantly more massive than most planets – between 13 and 75 times the mass of Jupiter. Only 2 to 3 per cent of known exoplanets are so hefty. But according to Stanimir Metchev of Western University in Ontario, Canada, "we truly don't know how low in mass the lowest-mass star-like object can be and how massive a planet can be". And in terms of actual size, most are not far off the diameter of Jupiter.

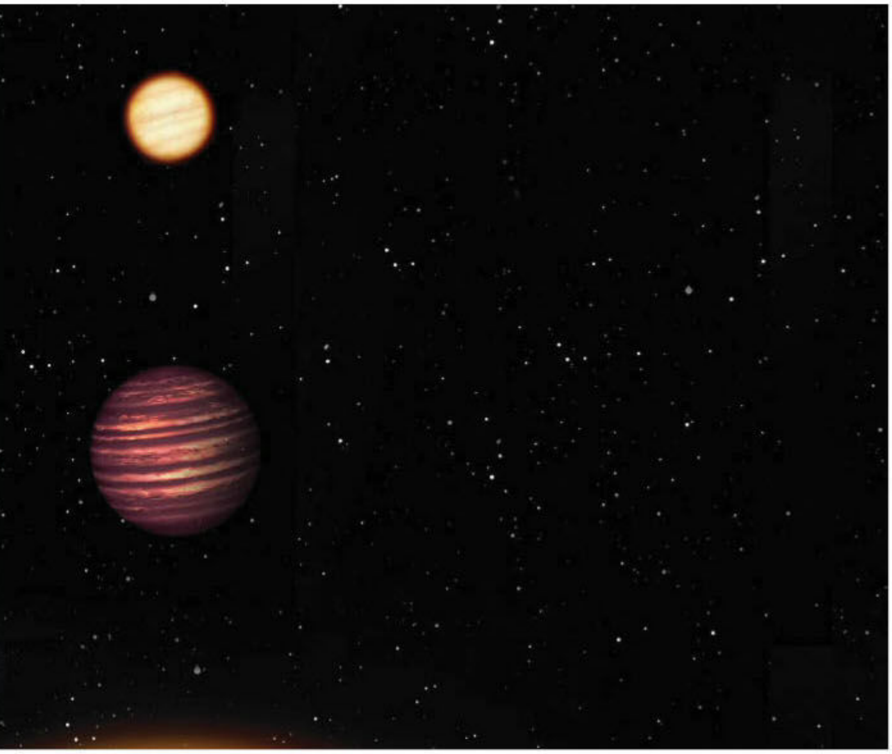
Cosmic relations

Brown dwarfs share many traits with gas giant planets, too, with a boiling atmosphere made of a toxic brew of carbon monoxide, hydrogen sulphide and water, or methane and ammonia. "The more data we collect, the more obvious the connection between brown dwarfs and planets," says Oppenheimer. Brown dwarfs, then, represent a bridge

Alien weather forecast

Brown dwarfs share many traits with gas giants such as Jupiter, including their size and occasionally temperature. This means their weather could provide clues to exoplanet climates





In the night sky, there is roughly one brown dwarf for every six stars

between stellar and planetary science.

Recently, we have encountered an intriguing new twist: they have weather. This realisation has sparked a shift in focus among brown dwarf aficionados, from simply searching the sky for more of them to characterising known objects in detail.

It was always suspected that brown dwarfs had clouds, because their internal heat would prompt gases to rise and then condense, as happens in the atmospheres of planets in the far reaches of our solar system. But recently we have been able to watch this weather change over time. In the past few years, astronomers realised that variations in the levels of infrared light emitted by brown dwarfs pointed to shifting patterns within the atmosphere. By training their telescopes on a target for months at a time, they deduced that certain changes in infrared emission were caused by huge storms.

If these brown dwarfs had a daily weather forecast, then the outlook would be "extreme". We know from studying the chemical composition of stars that the atmospheres of hotter brown dwarfs contain gaseous iron and silicate, which would eventually condense as it rises and cools. Imagine rain drops of molten iron, with swirling clouds made of hot grains of sand that gradually fall as silicate snow. "We think it would be very similar to the water cycle," says Mark Marley, also at the Ames Research Center.

Arguably, brown dwarfs have provided the first detailed insights into weather beyond our solar system. Weather on exoplanets, by contrast, is harder to see. "Exoplanets are too faint and we can't always get the spectra, because we need a huge telescope and a way to remove the starlight," says Sarah Casewell of the University of Leicester, UK. What we are learning from brown dwarfs could inform our knowledge of exoplanet climates, and help hone the techniques required to probe them. "Brown dwarfs are an excellent proxy for extrasolar giant planets," says Metchev.

For example, the fact that when a brown dwarf's atmosphere cools its cloud systems suddenly transform in character – often almost dissipating – suggests that we will see similar patterns on gassy exoplanets. "They've taught us that there is great diversity among substellar objects, and we should certainly expect even more as we study extrasolar planets," says Marley.

The coolest brown dwarfs have weather patterns we associate with our own planet – a few may even have clouds made of water vapour. "They are fully comparable in temperature to terrestrial zone planets in the solar system," says Metchev.

Other brown dwarfs promise to provide clues about the weather experienced by planets heated on only one side. Casewell, for example, studies systems in which a brown dwarf is paired with a white dwarf, locked so that only one side of the brown dwarf is bathed in radiation. "We're working on a lot of the atmospheric effects," she says. "Does only one hemisphere get hot? If not, are there large winds transferring heat from the hot side to the cold?" Understanding how such supersonic winds would affect weather patterns could help us work out the potential habitability of rocky exoplanets.

Perhaps the most tantalising revelation is that brown dwarfs can be accompanied by planets. Indeed, last year a team of astronomers claimed to have found the first terrestrial-mass planet orbiting a brown dwarf.

"It's quite possible that planets may form around brown dwarfs by standard planet-formation mechanisms," says Subhanjoy Mohanty of Imperial College London. Discovering such small, rocky planets orbiting a brown dwarf is not surprising, says Mohanty, since young brown dwarfs have less material surrounding them than more massive stars. Life, then, could exist on a world orbiting a brown dwarf.

Given that brown dwarfs have now finally come of age, perhaps we should stop trying to pigeonhole them as planets or stars. It's time to put them in a class of their own. ■

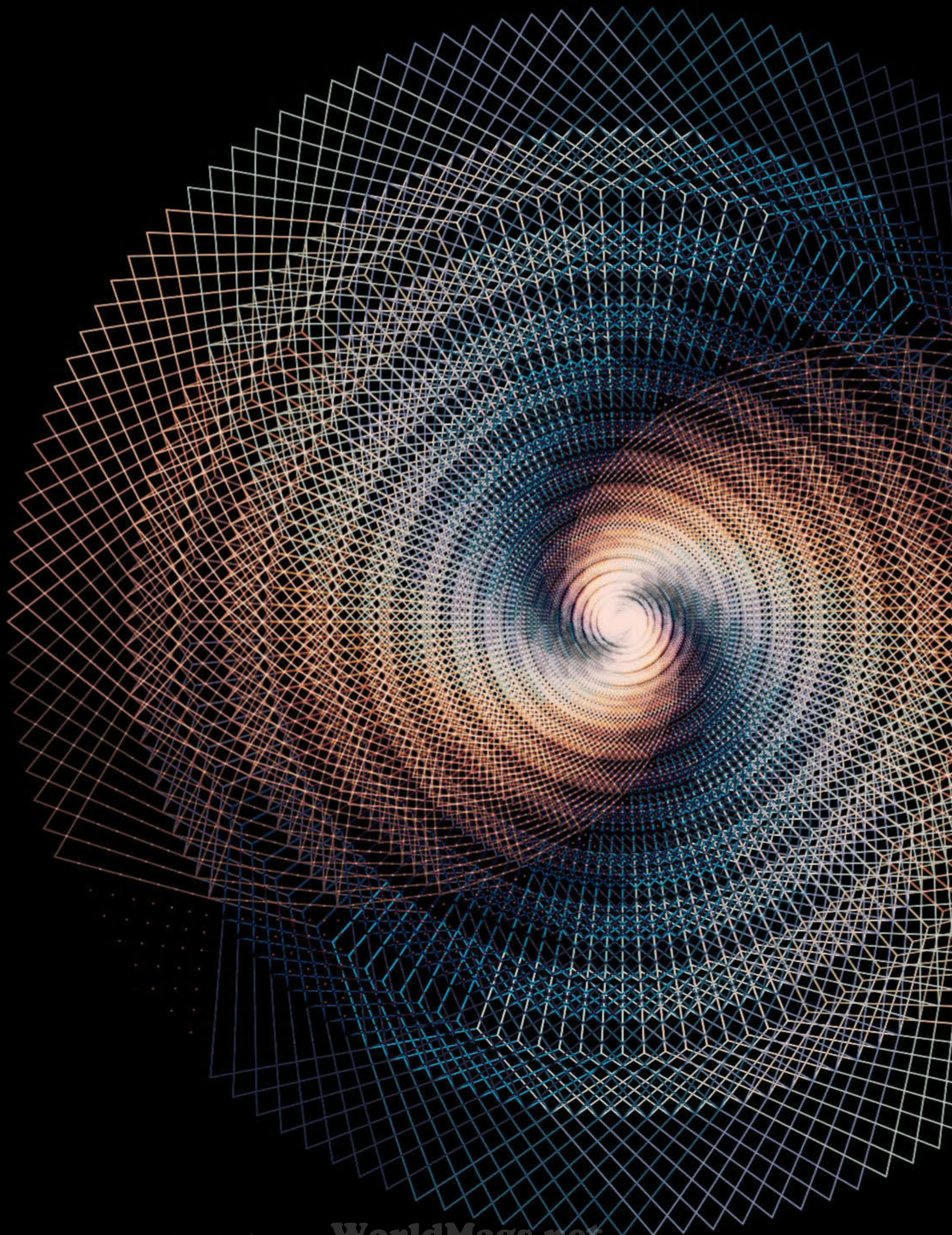
TRUE COLOURS

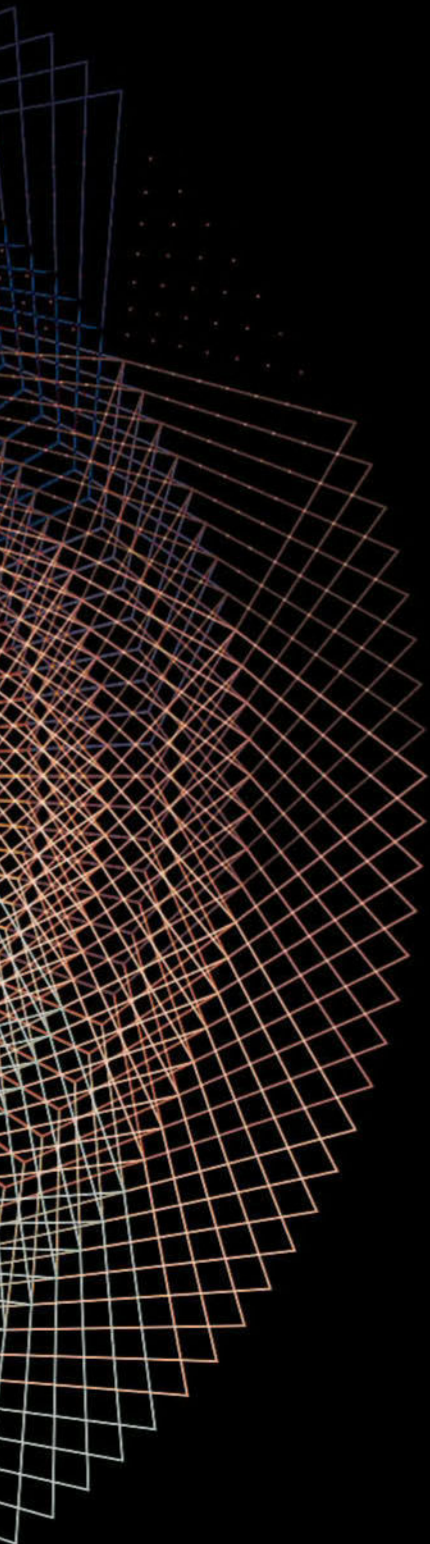
What colour is a brown dwarf? Well, not really brown.

Brown dwarfs received their drab name to differentiate them from other celestial objects: observed with optical telescopes, blue stars tend to be hot, red stars cooler. Brown was chosen as it is a mongrel shade, which some felt appropriate given that the colours of brown dwarfs were expected to be tricky to pin down.

When astronomers showcase images of brown dwarfs they use representative colours. Most brown dwarfs are observed using infrared telescopes, with various filters to record data at specific wavelengths. To produce a representative colour in a red-green-blue palette, astronomers assign the shortest wavelength filter they use to blue and the longest to red, and then stack them together. This commonly creates a magenta shade, although occasionally you get wilder colours, like green.

So what would a brown dwarf look like to the naked eye? Zoom past in a spaceship and you may well fail to see it because it would produce so little visible light. Peer closer, though, and you might see a faint glow in regions where it is still hot enough to produce light – but it might be more of a very dark orange.





ANDY GILMORE

Spiral galaxies are eye-catching beauties, but their oddly slimline forms could spell trouble for our theories of the cosmos, say Vanessa Thomas and Richard Webb

Battle of the bulge

THEY are the pin-ups of the cosmos – elegant, luminous spiral swirls that whisper to us the word "galaxy". It's how we think our Milky Way would appear if we could look down on it from above. Other captivating examples are not far away: our nearest large galactic neighbour, Andromeda, for instance, or the evocatively named Pinwheel galaxy.

Easy as these spiral beauties are on the eye, for cosmologists they are becoming something of a headache. As we survey the spiral galaxies around us more closely, nagging doubts are creeping in that some of the largest, most luminous examples in fact look rather too perfect. What's more, many of them seem to be in entirely the wrong place.

There could still be a simple explanation, in some unanticipated twist in the tale of how these galaxies formed. But as the evidence stacks up it is beginning to look like our favoured theory of the cosmos is due for a makeover – and with it our conception of the unseen "dark matter" that controls it.

In a cosmos like ours that consists largely of very little, galaxies are a not-so-minor detail that demands explanation. Any working theory of the universe's development must unravel how these huge agglomerations of matter formed from the featureless, homogeneous universe created in the big bang some 13.7 billion years ago.

Over time a convincing story has evolved, one known as the hierarchical model of galaxy evolution. Its starting point is quantum fluctuations in the matter density of the primordial cosmos, and in particular the doings of dark matter. This invisible substance is thought to account for three-quarters of all the universe's mass, or thereabouts. As the universe expanded and cooled, tufts of it began to condense, forming areas where gravity exerted a greater pull, sucking in more dark matter and also normal gas. Guided by the unseen hand of gravity, these clumps began to mingle, merge and combine over millions of years. That process set them spinning and flattened them out into ever-larger rotating discs of matter – the first galaxies.

This is not a pretty process. Across the universe today, we can see evidence of these violent events in action: sensational collisions between grown-up galaxies, and smaller ones ruthlessly shredded and consumed by their larger counterparts.

Where two mature galaxies combine, gas and stars are tossed this way and that, disrupting or destroying the original pristine, rotating discs and creating a huge spherical jumble. The near-featureless elliptical galaxies dotted around the present-day cosmos are the products of such mergers.

The basic spiral form can survive the smaller-scale events that punctuate most galaxies' histories, but clashes create a central "bulge" of upset stars that do not orbit neatly in one plane, but swarm almost randomly about the disturbed galaxy's core. About 70 per cent of the galaxies in our local universe have this characteristic shape – flat, spiralling arms radiating away from a central, spherical bulge.

That, at least, is what we thought. John Kormendy has long had a sneaking suspicion that this couldn't be the whole story. An astronomer at the University of Texas at Austin, Kormendy has racked up 35 years studying galaxy evolution. In that time, he and others have spotted oddly pristine spiral galaxies that seemingly have no bulge at their cores. They were isolated examples, however, and not enough to set alarm bells ringing. "They ›

could be explained away as the relatively few, relatively weird galaxies that happened not to have merged a lot," he says.

Then, in 2004, Kormendy teamed up with Ralf Bender of the Max Planck Institute for Extraterrestrial Physics in Munich, Germany. Their groups started to examine detailed images of large nearby spiral galaxies taken by the Hubble Space Telescope, backing them up with spectral observations from the University of Texas's Hobby-Eberly Telescope. The results, published in November 2010, were something of a shock. Of 19 large nearby spirals, at least 11 seemed to have no bulge, indicating that violent mergers didn't feature in their past. Among them were the seemingly exemplary Pinwheel galaxy – as well as the Milky Way.

What these galaxies do have is a bright central concentration of stars all crowded together. To a casual observer it looks like a bulge, but the orderly trajectory of the stars, plus areas of active star formation characteristic of quietly rotating discs, indicate that these stellar swarms do not in fact protrude from the galaxy's plane. It is a nicety that is easy to overlook if we don't have the luck of seeing a galaxy edge-on. "For many decades, they were misidentified as classical bulges," says Kormendy.

And this huge number of slimline, pristine spirals has morphed into a big problem for the hierarchical picture. To get as large as they are, they must have merged, yet "we don't know how to prevent bulge formation when galaxies grow big via mergers", says Kormendy. Jim Peebles, a cosmologist at Princeton University, agrees. "It is wildly unexpected in the standard model," he says.

It's not the only odd thing about these galaxies, either. Twenty-five years ago, Kormendy was among the first to propose that supermassive black holes play a significant part in galaxy evolution. We think that these black holes exist at the heart of most galaxies because matter near their cores seems to be whirling around a vastly dense agglomeration of mass. In the 1990s, Kormendy and others noted that bigger bulges tend to go hand-in-hand with bigger black holes, suggesting that the two develop in tandem.

The story runs something like this: as large amounts of new material fall into the centre of a galaxy during a merger, the black hole consumes some of it, growing in quick bursts.

In the pristine, bulge-free spirals, there are no mergers to feed the black hole in this way. And it seems there is also no connection between the mass of the central black hole and that of the galaxy's bright central regions, blowing apart the idea that a black hole evolves in lockstep with its environment. Some slimline galaxies seem to have tiny central black holes. The Pinwheel's, for example, is as little as one-thousandth the mass of the black holes of bulging galaxies of the same size. That leaves us with a rather messy picture. "Galaxies are complicated and we don't really understand how they form," says Peebles. "It's really an embarrassment."

Galaxy zoo

So what conclusions can we draw? The simplest, yet least satisfying, message is that the galactic past is inscrutably messy. Jonathan Feng, a particle physicist and cosmologist at the University of California, Irvine, thinks we may have to accept that there is no "one size fits all" explanation for how galaxies come to be. "Like people, galaxies have a wide variety of weird and wonderful histories, and these are reflected in the zoo of observed galaxy shapes and features," he says. Kormendy and his colleagues hope to explain those histories by looking at large clusters of galaxies, where as far as we can see all large galaxies do have bulges. If confirmed, that fact might indicate that it is a galaxy's gravitational environment – whether it exists in the crowded confines of a galaxy cluster or in a wide-open space between clusters – that is the crucial factor in determining the way it develops.

Peebles, though, wonders whether there might be more to it than that. He suggests that some central tenets of the hierarchical model must be abandoned or weakened, for these observations to make sense.

The key, he says, is to allow for some mechanism that enables galaxies to assume something approaching their final form quickly; far more quickly and smoothly than the bumpy hierarchical process with its continual collisions and mergers allows. If a galaxy merger occurs well into the galaxy's life, when many stars have had a chance to form, those stars get thrown around like pinballs, making a messy bulge inevitable. But if the gaseous structure of a spiral galaxy assembles through early mergers, before a great number of stars have had a chance to ignite, this gas can easily form into a pure, pristine disc.

What you end up with is a two-track picture. Collisions and mergers play their part in constructing some of the large spirals, those with large bulges. Bulge and black hole regulate one another, explaining the observed correlation between their masses. But a significant number of large spirals – perhaps even the majority – form quickly and then evolve, in Peebles's words, as "nearly isolated island universes". A corollary is that their central black holes grow in a slower, weaker process, pulling material in a little bit at a

"Galaxies are complicated and we don't really know how they form. It's really an embarrassment"

NASA/ESA/CXC/SSC/STSCI

time. That explains the apparent lack of correlation between their properties and those of the galaxy that hosts them.

While we didn't expect this complication, it has something else going for it. It might also explain why the pristine spirals we see are where they are.

There are hundreds of known galaxies within 26 million light years of our galactic centre. Oddly, nearly all of these galaxies crowd into just two-thirds of the volume available to them. The other third is a vast region called the Local Void, which contains a mere handful of galaxies. Trouble is, simulations based on the standard theory predict that the Local Void should contain about 19 galaxies, perhaps more.

Our galaxy and its neighbours are among those gathered like wallflowers along the edge of the void in a structure known as the Local Sheet. Yet three of the 10 biggest, brightest galaxies lie 6 million light years away from this structure. That's also a problem for the standard picture, which says they should appear in more crowded regions. Peebles and his colleague Adi Nusser from the Technion in Haifa, Israel, have calculated that the odds of finding the configuration that we do are well below 1 per cent.

"There is no shortage of alternatives to the cold dark matter embedded in our theory of cosmology"

That problem is resolved if some galaxies can evolve into their final forms faster. These rapidly forming galaxies would have sucked the area surrounding them dry of matter. With less matter within it to pull it together gravitationally, as the universe expanded following the big bang, this empty area would have expanded more rapidly, becoming ever bigger and emptier and eventually creating the Local Void with the galaxies collected around it that we see today.

But while the picture of fast-evolving galaxies has some compelling evidence to back it up, we still don't know the answer to a fundamental question: what is it that allows these galaxies to assemble so fast?

That might come down to dark matter's crucial role in fostering galaxies. The greatest concentrations of dark matter cradled the brightest galaxies and galaxy clusters. But if dark matter possessed different properties, that could have had dramatically changed how galaxies turned out, Peebles says.

The standard model of cosmology stands on the foundation of cold dark matter, which consists of a sea of particles that move around very little, if at all. That naturally produces a hierarchical picture, as such matter first gathers in small clumps, gradually merging to form large galaxies. It would be hard to conjure up something bigger straight off.

But it is not the only possibility. "If you want to consider alternatives to conventional cold dark matter, there is no shortage of possibilities," says Feng. If the stuff were a little warmer and faster-moving, for example, it would have a harder time converging into compact bundles, and would naturally form larger clumps, making mergers less essential – and possibly explaining how some galaxies could have grown without them.

One possible basis for warm dark matter is a "sterile" neutrino, a cousin of the elusive neutrino particles that we occasionally spy as they fly through the Earth without stopping. Neutrino-hunting experiments have in recent years seen ambiguous traces of these particles, which would be almost as light, and just as fleet of foot, as regular neutrinos but subject only to the force of gravity, making them even less reactive and even more difficult to pin down. Beyond sterile neutrinos, another possibility is that dark matter is created when heavier particles decay explosively, producing fast-moving, warm particles.

If dark matter comes in a different guise there will be consequences, though, Feng warns. "Since it is moving more quickly, it makes it harder to form small, dense regions," he says. That means there should be fewer smaller galaxies than the standard cosmology permits. That could tally with recent observations that the Milky Way has fewer satellite dwarf galaxies that we expect – although that could be just because we have not yet spotted them all. Besides, the existence of dwarf galaxies in itself implies we don't have a free hand in determining how dark matter looks, says Feng. "The fact there are some of them limits how much you can modify dark matter properties to explain other things," he says.

All that means we are left rather in the dark. "We need some measurements, some tests, of the nature of dark matter," says Peebles – until we do, we won't have any idea of its true influence on galaxy formation. That is one reason why so many astronomical eyes are fixed on the Large Hadron Collider at CERN near Geneva, Switzerland, as it embarks on a new and improved second run. Most models of dark matter predict particles that should be produced in its highly energetic collisions.

While we wait for new insights, the true life story of the pristine spirals eludes us. Only one thing is certain: it will probably have more twists than we had assumed. That might not be a bad thing, says Peebles. After all, our current prescriptions for things like dark matter are pretty basic. "Why shouldn't it be more complicated?" he asks. ■

The Pinwheel galaxy is far too perfect to be explained by cosmology

An "impossible" stellar explosion may provide an unexpected window on to the earliest days of the cosmos, says Stuart Clark

The star that time forgot

TIM GRAVESTOCK

AT FIRST, there didn't seem anything earth-shattering about the tiny point of light that pricked the southern Californian sky on a mild night in early April 2007. Only the robotic eyes of the Nearby Supernova Factory, a project designed to spy out distant stellar explosions, spotted it from the Palomar Observatory, high in the hills between Los Angeles and San Diego.

The project's computers automatically forwarded the images to a data server to await analysis. The same routine kicks in scores of times each year when a far-off star in its death throes explodes onto the night sky, before fading back to obscurity once more.

But this one did not fade away. It got brighter. And brighter. That's when human eyes became alert.

The supernova finally reached its peak brightness after 77 days. After 200 days – long after most supernovae have dwindled back into obscurity – it was still burning brightly. Only in October 2008, an unprecedented 555 days after it was first spotted, had it faded enough for the supernova hunters to call off their observations.

Digesting what they had seen took longer still. SN 2007bi, as dry protocol labelled the event, was one of the most extreme explosions ever recorded, of that there was no doubt. It was so intense that it didn't fit any model of how normal stars die. But then, it was rapidly becoming clear that, in life as in death, this had been no normal star.

If the interpretation of what popped up that April night is correct, this was a star that should not have existed, in a place where it should never have been. It was a mind-bogglingly massive star that was a throwback to a universe long since gone. It was a star that time forgot.

That picture began to emerge only after long months of monitoring the supernova's afterglow with the Samuel Oschin Telescope, a 67-year-old veteran atop Mount Palomar. This afterglow is powered by the decay of heavy radioactive elements generated in the runaway processes of nuclear fusion that occur during the initial explosion. The critical process is the decay of radioactive nickel, which quickly turns to cobalt, which in turn decays to iron, radiating gamma rays as it does so. The brightness and persistence of the afterglow reveal how much of these elements the supernova produced.

Plugging these observations into models of conventional supernovae brought a startling conclusion. To keep the supernova glowing that brightly, and for that long, the explosion must have produced 10 times more radioactive nickel than a normal supernova can muster – a discrepancy so huge that it demanded an explanation.

A clue to what was going on came in a few largely forgotten papers buried in journals from over 40 years ago. In the core of any massive star, the outward pressure of photons created in nuclear fusion reactions counters the weight of the material bearing down on it, preventing the star from collapsing in on itself. Sometimes, in massive stars many times the size of the sun, gravity can eventually overwhelm this photon pressure, initiating what is known as a core-collapse, or type II, supernova. That is one of two common types of supernova. The other, called type Ia, occurs when a dying white dwarf star accretes mass from a companion star and grows unstable, igniting in a final searing fireball (see diagram, page 125).

In the old papers, astronomers speculated on what might happen to cause a truly giant star – one bigger than about 200 suns – to go supernova. In this case, they calculated, the core of the star could eventually become so hot during nuclear fusion that photons would start to convert spontaneously into pairs of particles: an electron and its antimatter doppelgänger, a positron. This would rob the star of some of the photon pressure needed to support its outer layers, causing it to collapse in on itself in a gargantuan supernova that would vaporise the star. This final titanic burst of fusion would create vast quantities of heavy radioactive elements, far larger than a conventional supernova can produce. The astronomers called it a "pair-instability" supernova.

Implausible interloper

No supernova explosion answering to this description had ever been witnessed, and the idea remained a mere twinkling in the theorists' eyes. That is, it did until Avishay Gal-Yam, an astrophysicist at the Weizmann Institute of Science in Rehovot, Israel, and his collaborators started looking at SN 2007bi. The more they compared the data with various supernova models, the more they became convinced that the pair-instability model was the answer to the conundrum this explosion posed. "Only a pair-instability supernova can produce that much radioactive nickel," says Gal-Yam. With the model, they could even calculate how big the exploding star had been: a whopping 300 times the mass of the sun.

Problem solved? Not a bit of it. The ›

"We would dearly love to see one of these cosmic giants directly, if only to confirm the grounds for our own existence"

finding came with a massive sting in its tail: according to all our theories and all our observations, stars that big simply should not exist.

At least, they should not exist in the kind of universe we see around us today. In the decades since the pair-instability model was born, theory and some comprehensive sweeps of the night sky have combined to show that the composition of the modern cosmos prevents stars reaching such huge sizes. The presence of appreciable quantities of what astronomers call metals – elements heavier than hydrogen and helium – causes gas clouds to collapse speedily into "pocket-sized" stars. That is why most stars today are celestial minnows, containing less mass than our sun. The absolute upper limit on a modern star, theory and observations of our galaxy agree, lies at about 150 solar masses. A monster of 300 solar masses is an implausible interloper into this settled scene.

Things were different in early cosmic times, some 13 billion years ago in the pristine universe immediately after the big bang. Back then, solar giants ruled the roost. Only hydrogen, helium and trace amounts of lithium were floating around the cosmos, and much bigger quantities of these elements had to accumulate before they fell under the spell of gravity and were pulled together to form a star. As a result, the first stars in the universe were humongous, containing anything up to several hundred solar masses.

Fossil universes

Existing before proper galaxies had been able to form, these stars lived brief, wild lives of just a few million years as they furiously burned their vast stocks of hydrogen. Yet in their violent deaths, these stars were of huge significance. As theory has it, these explosions fused the first elements heavier than hydrogen, helium and lithium, seeding them throughout the universe. They provided the raw materials for the cosmos we see today: its galaxies, its sun-like stars, its planets and, in one insignificant corner at least, its life.

No one has ever seen these cosmic giants directly. We would dearly love to, if only to confirm the grounds for our own existence. Unfortunately, we can't. Even as they were sowing the seeds of the future cosmos, these megastars were precipitating their own demise. By increasing the metal content of the cosmos as they died, they destroyed the very conditions that nurtured them in the first place. By the end of the first few hundred million years after the big bang, metal levels were so high that stars of their like could never form again. Direct evidence for the existence of megastars lies in our universe's distant past, far beyond the horizon of even our most powerful telescopes.

Or does it? If SN 2007bi is what it seems, we might have found a get-out clause: a loophole that allows us to spy if not the first megastars, then something very similar. Against the odds, the cosmic trailblazers may have lived on into the modern universe. But how?

The secret lies in where this supernova was situated: an otherwise unassuming dwarf galaxy some 1.6 billion light years away from Earth. Dwarf galaxies, as their name suggests, are runtish structures that never made it to full size. Whereas a fully formed galaxy such as our own Milky Way contains several hundred billion stars, a dwarf galaxy can have as few as just a couple of million.

Observations of the distant universe show that dwarf galaxies were once much more prevalent. "We know that the first galaxies to form were dwarfs," says Nils Bergvall of the Uppsala Observatory in Sweden. The idea is that these were the basic blocks that built up to form the much larger galaxies of today.

We also know that dwarf galaxies, even those relatively nearby which we can see as they were in comparatively recent cosmic time, have just 5 to 10 per cent of the metals that our sun has – or markedly less than one-hundredth of their total mass. The earliest dwarf galaxies may have had even less.

We have been slow to grasp the implication: that the tiniest dwarf galaxies could be pristine chunks of the early universe, preserving its composition and conditions in a cosmos that has long since moved on. Their degree of preservation could be the result of their sheer dwarfishness: because gravity within them is weaker than within a normal galaxy, a supernova exploding within it will fling the metal-rich products outwards at such speed that they mostly escape altogether.

If the original conditions of the universe were preserved in these dwarf galaxies, there would be no reason why further waves of megastars should not continually form and die within them throughout cosmic time. If it is the absence of metals that determines stellar size, behemoth stars are not restricted to the furthest reaches of the universe: they could be found in any dwarf galaxy with a low enough metal content, including places well within reach of our telescopes. It is a line of reasoning that the identification of SN 2007bi now seems to support in spectacular fashion.

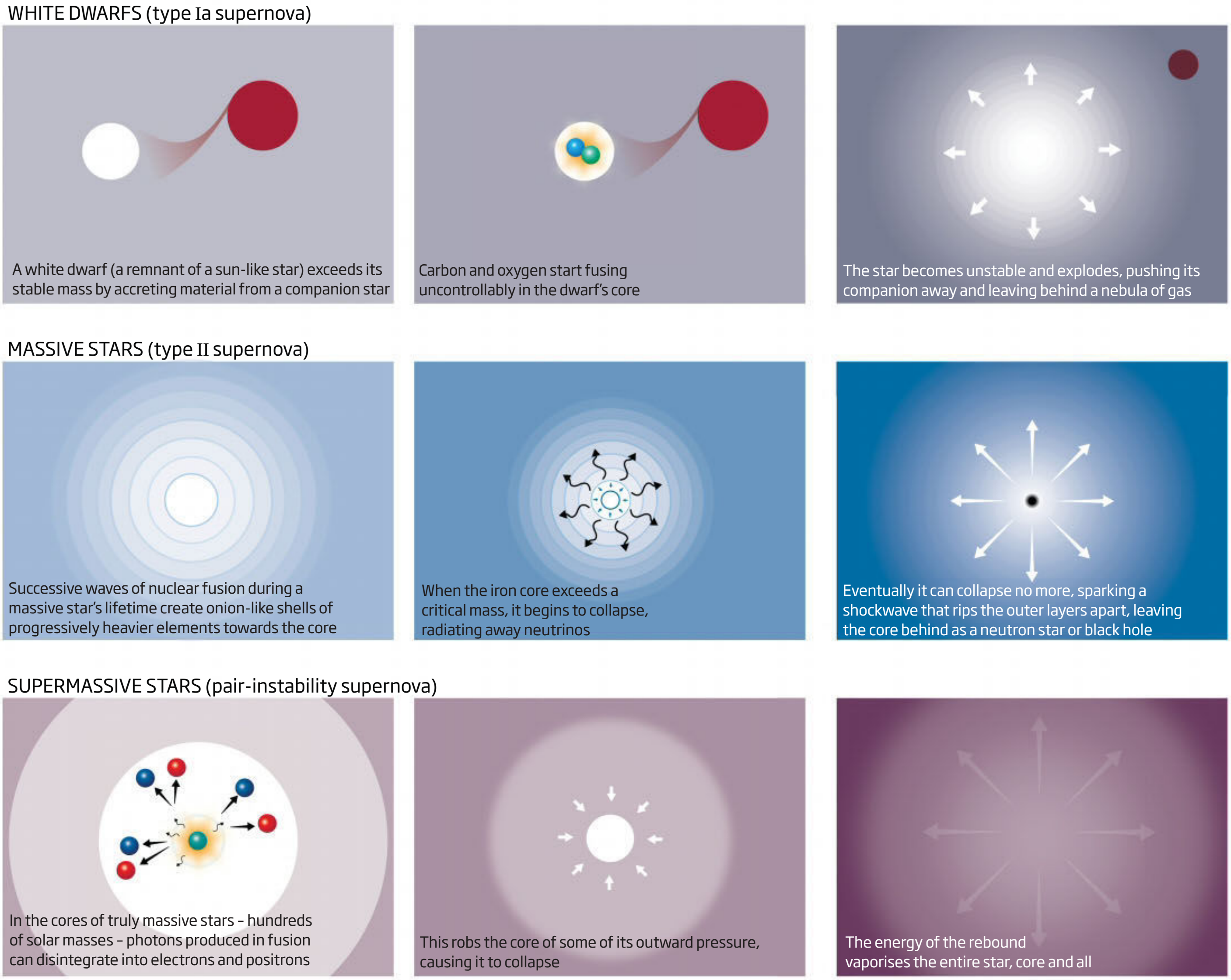
The discovery of a nearby population of megastars in what amounts to suspended animation would have huge implications for stellar science. We do not understand the processes of star formation and death as well as we would like to think. "It is surprisingly difficult to get the models to agree with the observations," says Gal-Yam. He cites the example of gold, the abundance of which in the universe essentially defies explanation, although most astronomers assume it must somehow be made in supernovae. To find some answers, we might need to look no further than nearby dwarf galaxies.

But wait a moment. If these huge living fossils have always been lurking on our cosmic doorsteps, how come we have not seen them before now? Stars that big would surely be hard to overlook, either during their tempestuous lives or spectacular deaths. Yet apart from one peculiarly luminous supernova in 1999, we have never seen anything that looks like SN 2007bi.

Part of the explanation, says Alexei

Going out with a bang

How a star's life ends depends on its size



Filippenko of the University of California, Berkeley, is that we have been looking in the wrong places. "Telescope time is precious, and in a pathetic dwarf galaxy there are not that many stars, so not that many opportunities for one to go supernova," he says. Astronomers have understandably focused their attention on the big galaxies that are richly stocked with stars.

Tantalising glimpse

That is now changing as fast robotic sky searches, such as the Palomar Transient Factory based at the observatory that first spotted SN 2007bi, swing into action. Such projects make no judgement about where best to look; they just keep their electronic eyes open for anything that is changing in the sky. This new strategy has already borne fruit. "We are now tracking a number of supernovae that could also turn out to be pair-instability supernovae. But we want to be absolutely certain before we announce," says Filippenko.

Direct observations of any living megastars lurking out there are more tricky. Giant stars with their huge stocks of hydrogen and helium fuel would be so hot that most of their energy would be emitted as ultraviolet light, which is absorbed by Earth's atmosphere before it reaches ground-based telescopes. "Without seeing the ultraviolet, these stars will just hide away and look like ordinary high-mass stars," says Gal-Yam.

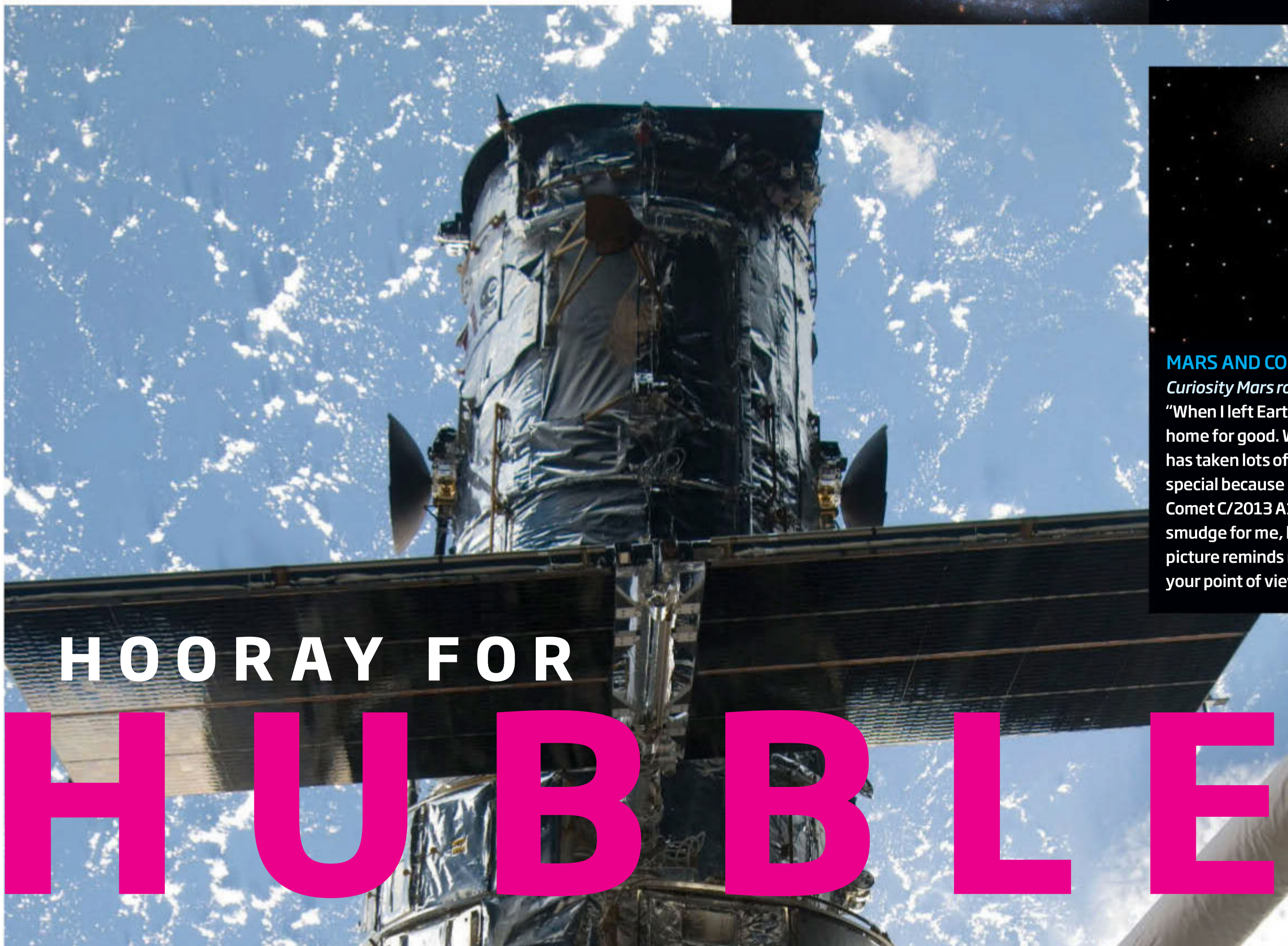
Because astronomers have traditionally believed that there is little of interest to see at ultraviolet wavelengths, there are no general-purpose ultraviolet space telescopes, either. The Hubble Space Telescope can see at these wavelengths, but the kind of painstaking programme to map relatively nearby dwarf galaxies would mean tying it up for thousands of hours of observation time. Fortunately, Gal-Yam's proposals to carry out this type of research have met with approval, and the analysis is underway.

Hubble was serviced for the final time in 2009, and attention is now switching to its replacement, NASA's James Webb Space Telescope, which is scheduled for launch in 2018. But this telescope has no ultraviolet capability. "Once Hubble is gone, we are going to be totally blind," says Gal-Yam. "There is an urgency about doing this work."

At it stands, that April supernova could have been a tantalising and wholly unexpected glimpse into a universe we thought we would never see, that of the first stars, the cosmos makers. That would be an explosion to truly blow our minds. ■

HOORAY FOR HUBBLE!

FOR 25 YEARS, THE HUBBLE SPACE TELESCOPE HAS DELIVERED STUNNING IMAGES OF THE COSMOS. TO CELEBRATE ITS QUARTER CENTURY IN JUNE 2015, *NEW SCIENTIST* ASKED RESEARCHERS, AN ASTRONAUT AND EVEN A MARTIAN ROVER TO SELECT THEIR FAVOURITES



SPIRAL GALAXY NGC 1300

Zolt Levay, *leader of the Hubble imaging group at the Space Telescope Science Institute in Baltimore, Maryland*

"This is the prototypical example of a barred spiral galaxy… Amazing details appear in the colour composite: beautifully resolved spiral arms and dust lanes to the bright nucleus. And the disc is transparent enough to see distant background galaxies, which provides a dramatic feeling of depth."

MARS AND COMET SIDING SPRING

Curiosity Mars rover, *@MarsCuriosity*

"When I left Earth in 2011, I knew Mars would be my home for good. While the Hubble Space Telescope has taken lots of images of the Red Planet, this one is special because I know I'm on the surface, working. Comet C/2013 A1 Siding Spring appeared as just a smudge for me, but to Hubble it was glorious. This picture reminds me that sometimes you must change your point of view to see things as they really are."

EAGLE NEBULA

Jeffrey Hoffman, *astronaut*

"Despite having become almost a cliché, the Eagle nebula still gives me goosebumps when I realise that we are seeing the actual birth of stars. It's biblical in its impact: 'Let there be light!'"

GALAXY CLUSTER ABELL 68

William Borucki, *former principal investigator of the Kepler planet hunter*

"The image I find most compelling is that of galaxy cluster Abell 68… I get a very eerie feeling when I see all those galaxies and realise that we have not picked up any sign of life from any exoplanet orbiting any of the billions of billions of stars those galaxies contain."

AN IMPOSSIBLE TASK

Neil deGrasse Tyson, *astrophysicist and director of the Hayden Planetarium in New York*

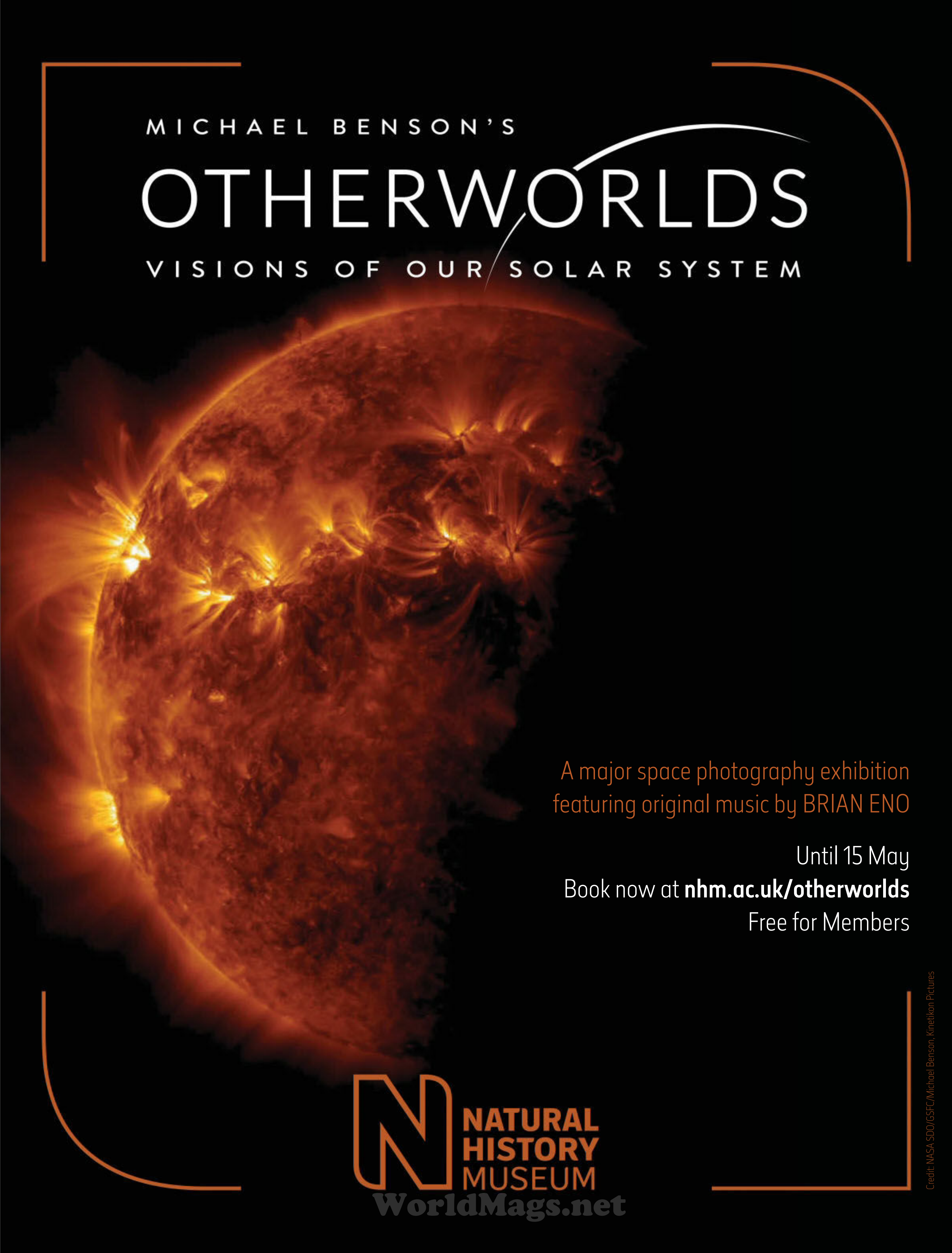
"It's like picking your favourite child. I can't do it. What is certain, however, is that nobody ever required a caption to appreciate the images. They convey their own majesty and splendour without it."

HELIX NEBULA

Barbara Mikulski, *US senator for Maryland*

"I keep a huge print of the 'Eye of God' Helix nebula hanging in my office… Every time I stand in front of it, I'm reminded not just of the insight and beauty that Hubble brought home, but also of the people – the engineers, scientists, technicians, support staff, cafeteria workers and custodians – who have all done so much to advance our understanding of the cosmos."

THERE ARE FIVE DIFFERENT TYPES OF BOREDOM...
AVOID THEM ALL
Subscribe now for less than £2 per week, and discover a whole world of new ideas and inspiration
Visit newscientist.com/8810 or call 0300 333 9470 or +44 (0) 1444 475636 and quote offer 8810
New Scientist
#LiveSmarter
CYRUS CORNUT/DOLCE VITA/PICTURETANK
WorldMags.net


MICHAEL BENSON'S
OTHERWORLDS
VISIONS OF OUR SOLAR SYSTEM
A major space photography exhibition featuring original music by BRIAN ENO
Until 15 May
Book now at nhm.ac.uk/otherworlds
Free for Members
NATURAL HISTORY MUSEUM
Credit: NASA SDO/GSFC/Michael Benson, Kinetikon Pictures